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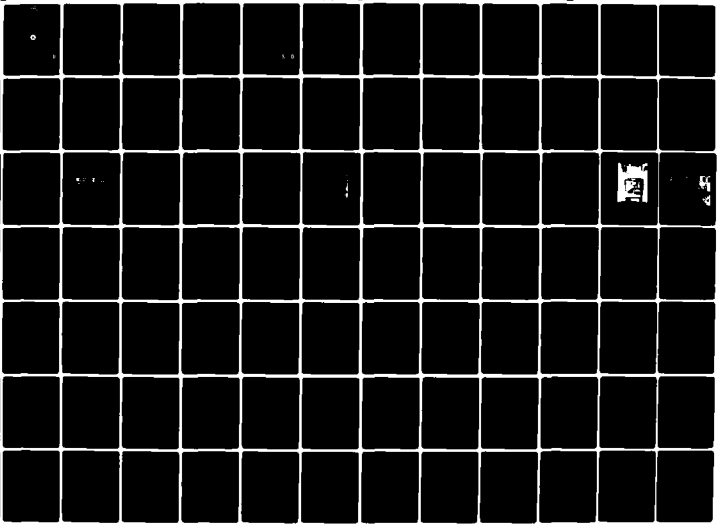

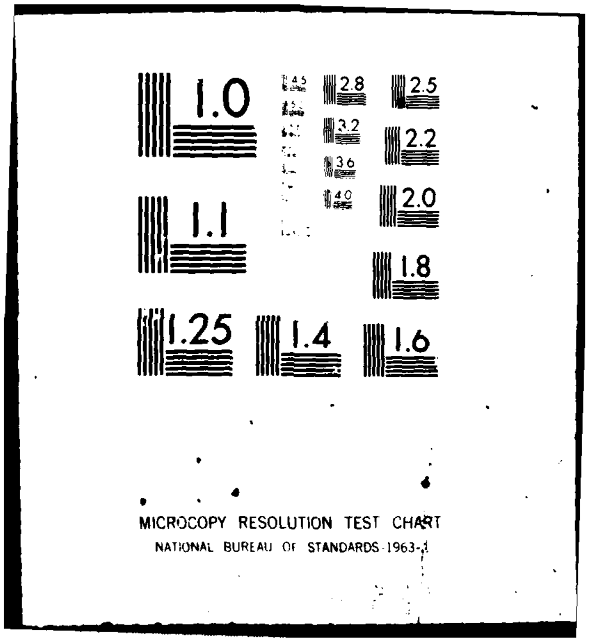
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Report No. FAA-RD-80-28

LEVEL II

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WEST COAST LORAN-C FLIGHT TEST

ADA084039

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E.D. McConkey

March 1980

Final Report

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16. Abstract

A flight test program was flown within the coverage area of the West Coast Loran-C chain during June and July 1979. The purpose of the test was to add to the growing statistical data base that will be used to assess Loran-C as a supplement to, or replacement for, the present VOR/DME navigation system. The test objectives were to: 1) Evaluate the West Coast Loran-C chain by quantifying navigation and position errors within its coverage area; 2) Test Loran-C as a non-precision approach aid in mountainous conditions, using a commercially available Loran-C receiver/navigator, in this case a Teledyne TDL-711; 3) Record the effects of bias shifts and station outages on overall accuracy and approach procedures, especially near a baseline extension; 4) Calculate the absolute flight technical error (FTE) during Loran-C approaches using a typical general aviation aircraft.

The main conclusions of the test were: The West Coast Loran-C chain appears stable and dependable. Time difference errors were consistent and related to signal propagation differences over land and over water; the TDL-711 was found to be easy to operate, giving stable and repeatable course guidance, although susceptible to random loss of track, a problem which may be software related. The system did not accurately calculate cross track deviation and distance to waypoint. Without needed hardware, software, and/or procedural changes, Loran-C may not meet the RNAV non-precision approach requirements of AC 90-45A. The test approaches were easily flown, although the nav system had typical pitfalls: Errors in waypoint entry or station (triad) selection could have a catastrophic effect, an independent nav crosscheck of position is needed, and any ATC-required maneuvering can increase pilot workload significantly.

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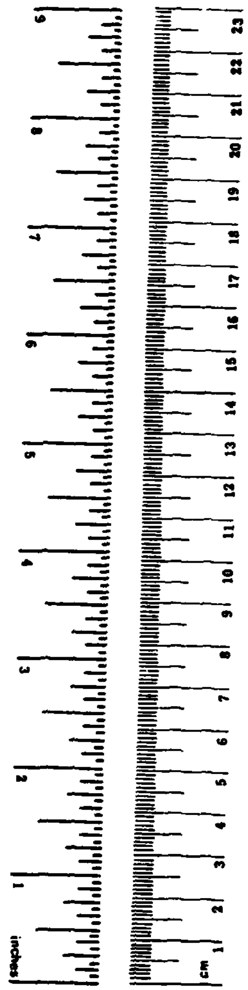
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

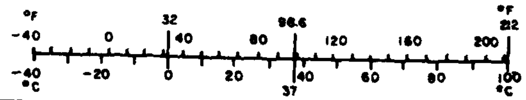
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This study was conducted under Task 13 of contract DOT-FA75WA-3662, "Technical Assistance for the Development and Evaluation of Airborne VLF Navigation Systems", for the Federal Aviation Administration, Systems Research and Development Service. The FAA Technical Monitor was Mr. George Quinn, ARD-311. The program manager for SCI (Vt.) was Dr. Donald W. Richardson, Division President. The following employees of SCI (Vt.) contributed to the conduct of this study in the following areas.

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Edwin D. McConkey	--	Loran-C Propagation Analysis, Author
Donald W. Richardson	--	Test Planning, Subject Pilot
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ABBREVIATIONS AND ACRONYMS

AC	-	ALTERNATING CURRENT
AGL		ABOVE GROUND LEVEL
AM	-	AMPLITUDE MODULATION
ARINC	-	AERONAUTICAL RADIO, INC.
ASCII	-	AMERICAN STANDARD CODE FOR INFORMATION INTERCHANGE
ATC	-	AIR TRAFFIC CONTROL
BIT	-	BINARY DIGIT
BYTE	-	AN 8 BIT COMPUTER WORD
CAT	-	COMPUTER ALONG TRACK ERROR
CCT	-	COMPUTER CROSS TRACK ERROR
CDI	-	COURSE DEVIATION INDICATOR
CDU	-	CONTROL DISPLAY UNIT
CRT	-	CATHODE RAY TUBE
CTD	-	CROSS TRACK DEVIATION
COMM	-	COMMUNICATIONS
DC	-	DIRECT CURRENT
DME	-	DISTANCE MEASURING EQUIPMENT
FAA	-	FEDERAL AVIATION ADMINISTRATION
FAF	-	FINAL APPROACH FIX
FTE	-	FLIGHT TECHNICAL ERROR
GDOP	-	GEOMETRIC DILUTION OF PRECISION
HP	-	HOLDING POINT
Hz	-	HERTZ
IAF	-	INITIAL APPROACH FIX
ICAO	-	INTERNATIONAL CIVIL AVIATION ORGANIZATION
IF	-	INTERMEDIATE FIX
ILS	-	INSTRUMENT LANDING SYSTEM
KHz	-	KILOHERTZ
KW	-	KILOWATT
LAT/LON	-	LATITUDE/LONGITUDE
L-BAND	-	DME FREQUENCY BAND
LOP	-	LINE OF POSITION
LORAN-C	-	LONG RANGE NAVIGATION (VERSION C)
MAP	-	MISSED APPROACH POINT
MDA	-	MINIMUM DESCENT ALTITUDE
MS	-	MICROSECOND
MSE	-	MEAN SQUARE ERROR
MSL	-	MEAN SEA LEVEL

NAT	-	NAV ALONG TRACK ERROR
NAV	-	NAVIGATION
NBS	-	NATIONAL BUREAU OF STANDARDS
NCT	-	NAV CROSS TRACK ERROR
NDB	-	NON-DIRECTIONAL BEACON
NM	-	NAUTICAL MILE
PROM	-	PROGRAMMABLE READ-ONLY MEMORY
RAPPS	-	REMOTE AREA PRECISION POSITIONING SYSTEM
RDU	-	REMOTE DISPLAY UNIT
RMS	-	ROOT-MEAN-SQUARE
SNR	-	SIGNAL TO NOISE RATIO
TACAN	-	TACTICAL AIR NAVIGATION
TD	-	TIME DIFFERENCE
TSCT	-	TOTAL SYSTEM CROSS TRACK ERROR
VHF	-	VERY HIGH FREQUENCY
VOR	-	VHF OMNI RANGE
VOR/DME	-	VHF OMNI RANGE WITH DISTANCE MEASURING EQUIPMENT

1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES

There were four major objectives of the West Coast Chain Loran-C Flight Test:

- Evaluate the suitability of Loran-C for overland air navigation by quantifying navigation and position accuracy at three selected geographical locations within the coverage area of the West Coast Loran-C Chain.
- Test the feasibility of Loran-C as a non-precision approach aid in mountainous areas, using the Teledyne TDL-711, a commercially available Loran-C receiver/navigator, as the primary air navigation/approach guidance system.
- Record the effects of bias shift and station outage on overall accuracy and on approach procedures, particularly on or near a baseline extension.
- Calculate absolute Flight Technical Error (FTE) during Loran-C non-precision approaches using a fixed-wing aircraft typical of general aviation.

1.2 APPROACH

The method used to achieve the objectives was to install an electronics package, containing both Loran-C and ground truth measurement equipment, in a contractor-supplied Piper Aztec light, twin-engined aircraft. The aircraft was then used in a total of 24 non-precision approaches flown at five selected locations:

- South Lake Tahoe, California
- Klamath Falls, Oregon
- Grand Junction, Colorado
- Reno, Nevada (Reno International)
- Reno, Nevada (Stead Airport)

The test locations provided a comprehensive, worst-case mixture of terrain, Loran-C geometry, and fringe area problems against which the characteristics of Loran-C and the performance of the TDL-711 could be tested. The formal test approaches were flown at South Lake

Tahoe, Klamath Falls, and Grand Junction. The two Reno airports were used for system checkout flights.

Inflight test data were collected using digital information produced by the TDL-711 and data acquired from the Remote Area Precision Positioning System (RAPPS), which polled multiple DME beacons (both existing and portable) to independently fix aircraft position using multilateration.

The contractor's two-pilot aircrew flew all the approaches, alternating as pilot flying the approach under an instrument "hood", and as co-pilot/observer maintaining a safety watch and recording salient operational events to later corroborate the results extracted from the digital data. The pilots' subjective operational evaluation of the Loran-C system, both in terms of the overall characteristics of Loran-C as well as specific evaluation of the Teledyne TDL-711, forms a significant product of the test.

1.3 RESULTS

The evaluation of the TDL-711 contained in this report is intended to apply to the specific equipment used in the test and its operation during the test period. As of this writing, Teledyne has reported that many of the software-related problems noted during the test have been corrected. However, there are as yet no test data to corroborate this information. A detailed discussion of the data analysis is contained in Sections 5.0 and 6.0. The following is a summary of the results by test objective.

- Some inherent problems with Loran-C were evident during the test. Bias shifts (a warping of the Loran grid), geometric dilution of precision caused by unfavorable line of position crossing angles, and signal propagation errors all contributed to inaccuracies, and are problems yet to be solved. Bias shifts, in particular, were largely responsible for along track and cross track inaccuracies that exceeded AC90-45A approach requirements.

  Two of the test locations, Klamath Falls and Grand Junction, were intentionally selected because they were located on the baseline extensions of certain station pairs within the West Coast Chain. In each of these locations, due both to

the high GDOP characteristic of baseline extension locations and to propagation model errors, the navigator was unable to accurately fix its location. At Grand Junction with the Fallon-Middletown-Searchlight triad, position errors of as much as 10 to 15 nm were experienced. At Klamath Falls, using the Fallon-Middletown-Searchlight triad, these factors combined to produce time differences which the navigator could not resolve into a line of position. A further, and more detailed, discussion of these problems and their effects is contained in Section 6.0.

- Loran-C did not fully meet the minimum accuracy requirements of AC90-45A for non-precision approaches using a non-VOR/DME based navigation system.

  Due to biases mentioned above, the results were as shown in Table 1.1.

Table 1.1 Navigator Sensor Error Performance

	CROSS TRACK		ALONG TRACK	
	Mean	2σ	Mean	2σ
AC90-45A REQS	---	.30	---	.30
Klamath Falls (FMG)*	.07	.24	.04	.13
Lake Tahoe (FMS)	-.33	.11	.39	.27
Lake Tahoe (FMG)	.17	.15	-.48	.22
Grand Junction (FGS)	-.21	.40	.00	.15
Reno (FMS)	-.11	.09	.76	.33
Stead (FMG)	.20	.45	.22	.26
Stead (FMS)	-.85	.19	-.18	.37
Test Aggregate	-.10	.49	.14	.71

*F - Fallon, Nev. G - George, Wash.
M - Middletown, Cal. S - Searchlight, Nev.

The mean and 2σ cross track and along track error results are shown for each location at which data were recorded, including Reno International, at which three equipment checkout approaches were flown, and Reno/Stead where two tracking passes were flown.

A certain bias, or apparent shift of the Loran lines of position, is reflected in the mean figures in both categories. The individual 2σ figures are, for the most part, well within the AC90-45A maximum errors (the higher 2σ figures at Reno and Stead are based on a much smaller number of data points but are included to conform with the body of the report). However, when the results are aggregated, the biases reflected in the mean figures tend to moderate while contributing to the larger 2σ aggregate numbers — the 2σ aggregate deviation is larger than any of the individual deviations.

There are a number of techniques which might be used operationally to neutralize these biases:

1) Using measured TDs for waypoint coordinates
2) Using measured lat/lons for waypoint coordinates
3) Implementing a differential Loran concept
4) Improving the propagation model in the navigator

Assuming that one or more of these approaches were sucessfully applied and the biases could be eliminated, then the aggregate results would be as shown in Table 1.2, well within the AC90-45A requirments.

Table 1.2 Navigator Sensor Error Corrected for Bias

	CROSS TRACK		ALONG TRACK	
	Mean	2σ	Mean	2σ
AC90-45A	---	.30	---	.30
Loran-C Test Aggregate	.00	.21	.00	.23

- The TDL-711 was generally simple and straightforward to operate and the mode selector and keystroke sequences used to manipulate the system were logical and clear. However, there were some problems. The keys had a tendency to stick when depressed due to a physical characteristic of the keys themselves. Also, a diagnostic mode available to the operator was found to over-write internal memory locations containing navigation information, which centered the CDI needle with no warning indication. This diagnostic function is not part of the normal operation of the TDL-711, but it is available to the operator in flight and it can be entered inadvertently since the mode selector/keystroke sequence to select it can be duplicated under certain conditions of normal operation.

- The -711 was found to convert TDs into lat/lons very accurately (see Table 1.3).

Table 1.3 Lat/Lon Coordinate Conversion Errors (Feet)

	NO. POINTS	LATITUDE		LONGITUDE	
		Mean	σ	Mean	σ
TEST TOTAL	737	71'	86'	-32'	29'

However, conversion from lat/lon to along and cross track coordinates was inaccurate (see Table 1.4), and in some cases the coordinate errors were of the same magnitude as the raw Loran-C errors themselves.

Table 1.4 Along/Cross Track Coordinate Conversion Errors (nm)

	NO. POINTS	CROSS TRACK		ALONG TRACK	
		Mean	σ	Mean	σ
TEST TOTAL	615	.04	.15	-.04	.04

- The accuracy of the coordinate conversion results was further degraded because the -711 navigator did not account for propagation factors typical of the areas in which the test was conducted (propagation over land rather than seawater). Had a conductivity correction of .005 mhos/meter been used, the root mean square of the mean time difference errors for all the test locations could have been reduced from 2.41 μs to .85 μs.
- The system was also subject to random breaks in lock (indications from the navigator that the information presented was unreliable). The frequency of these occurrences is shown in Table 1.5. The average duration of the breaks in lock was 43.33 seconds. In most of the cases, the reasons for the breaks in lock could not be determined from the available test data. This problem, as well as those of coordinate conversion and diagnostic functions, appears to be software related.

Table 1.5 Frequency of Breaks in Lock

NO. OF APPROACHES	NO. OF BREAKS IN LOCK	NO. OF BREAKS IN LOCK/APPROACH
24	15	.625

On the whole, the TDL-711 gave steady guidance that was sensitive without being jumpy and the Loran deviation needle was easy to fly accurately, a confidence builder for the pilot.

Some of the information provided by the TDL-711 (such as track angle error, desired track angle, track angle, and cross track distance) was never used and appeared to be unnecessary in the approach environment.

- Bias shifts were not constant throughout the chain, but varied from test location to test location. The effects of their existence and magnitude also varied with approach course. A more detailed discussion of bias shifts and their effects is contained in Section 6.0.
- Statistical calculation of Flight Technical Error (FTE) revealed that the mean FTEs measured ranged from a high of .14 nm to a low of -.02 nm, and the standard deviation ranged from .34 nm to .06 nm. The small size of these figures is directly attributable to the steady course guidance provided by Loran-C and the TDL-711.

1.4 CONCLUSIONS

The conclusions developed as a result of the West Coast Loran-C flight test can be grouped in three general areas: Loran-C chain performance, performance of the TDL-711, and Loran-C as an approach aid.

1.4.1 Loran-C West Coast Chain Performance

Based on the time difference and signal-to-noise ratio data recorded during the test, Loran-C chain performance was very good (only two momentary losses of station tracking occurred inflight). The West Coast chain was stable and well-controlled with excellent repeatability (similar results were obtained at South Lake Tahoe on both 7 July and 26 July). Errors which were measured were consistent (biases) rather than random, and may have been related to propagation delay factors. Time difference bias errors would be reduced if a land conductivity value were included in the propagation model within the navigator. There were, however, variabilities in time differences during the approaches, as well as grid warpage to a minor extent and jitter in some of the measurements, but conclusive evidence could not be found to pinpoint causes for these effects.

1.4.2 Performance of the TDL-711

In general the TDL-711 was easy to operate and imposed no undue burden on the flight crew. Guidance information was remarkably stable when the navigator was locked on, however the unit would unexpectedly

lose track of its internal latitude and longitude solution and revert to a search mode (usually lasting 30 seconds or more). These random occurrences could be disconcerting to the flight crew and would offset the confidence engendered by the stability of the course guidance. The loss of track problem is presumably software related.

The navigator very accurately calculated latitude/longitude from measured TDs, using the U.S. Coast Guard standard propagation model. But errors of up to one quarter mile appeared in cross track deviation and distance to waypoint calculations. Although none of these errors exceeded AC90-45A limits for RNAV approach capability, when combined with errors in the Loran-C system, AC90-45A criteria were even more difficult to meet than would otherwise have been the case.

The TDL-711 took about two minutes or less to acquire the chain and converge on a solution, not an unreasonable time and not likely to be a consideration during an approach since a chain change would not be a routine procedure.

This evaluation of the TDL-711 is meant to pertain to a particular piece of equipment operating within a particular Loran-C chain coverage area. The results are not meant to be absolutely representative of Loran-C in general. Some problems related to the TDL-711 software have reportedly been corrected since the test.

1.4.3 Loran-C As An Approach Aid

Loran-C may not meet the approach category requirements of AC90-45A given present technology, unless hardware, software or procedural modifications are made. Since operational techniques are available to neutralize locally consistent biases, this problem appears solvable. The test results showed that approaches can be made with ease. Loran-C, however, suffers the same drawback as other area coverage systems in that errors in specifying waypoint location or station (in this case, triad) selection could be castastrophic. Some independent navigational crosscheck would be highly advantageous when available.

Despite the above-mentioned reservations, Loran-C has promise as an enroute navigation and approach aid, particularly at remote locations unable to support an instrument landing system.

2.0 INTRODUCTION

2.1 LORAN-C

Loran-C is a passive navigation system requiring no transmissions from the receiving entity. The system is built around groups of fixed, ground transmitters. Each group, called a chain, is made up of a master station and two to four secondary stations. Each station broadcasts a series of synchronized, low frequency pulses throughout its coverage area. The receiver/processor uses these pulses to calculate time-differences, or TDs. The TD is a measure of the elapsed time between the arrivals of a master station pulse and a secondary station pulse. A line of position (LOP) is then established. The LOP is a hyperbolic curve between the two stations along which the TD, or elapsed time difference, is constant. Two such LOPs cross at the receiver's location (see Figure 2.1). Loran stations within a chain are generally 400 to 700 miles apart.

2.2 LORAN-C FLIGHT TESTING

The flight testing of Loran-C as a non-precision approach aid is a logical outgrowth of the recent increase in demand for air navigation capability outside the coverage of the present VOR/DME system. Offshore oil rig operators and suppliers need both accurate enroute navigation capability and a viable non-precision approach aid for efficient, all-weather day-to-day operations. Sportsmen and vacationers in ever increasing numbers want access to mountainous resort areas and, therefore, need air navigation capability that is free from terrain restrictions on coverage and accuracy. Police and rescue organizations need to be able to rendezvous at remote emergency sites efficiently and accurately. Loran-C is being considered as one system with the potential to meet these navigation needs.

2.3 OBJECTIVES

The purpose of this flight test was to add to the growing amount of statistical information that will be used to accurately assess Loran-C as either a supplement to, or replacement for, the present VOR/DME navigation system.

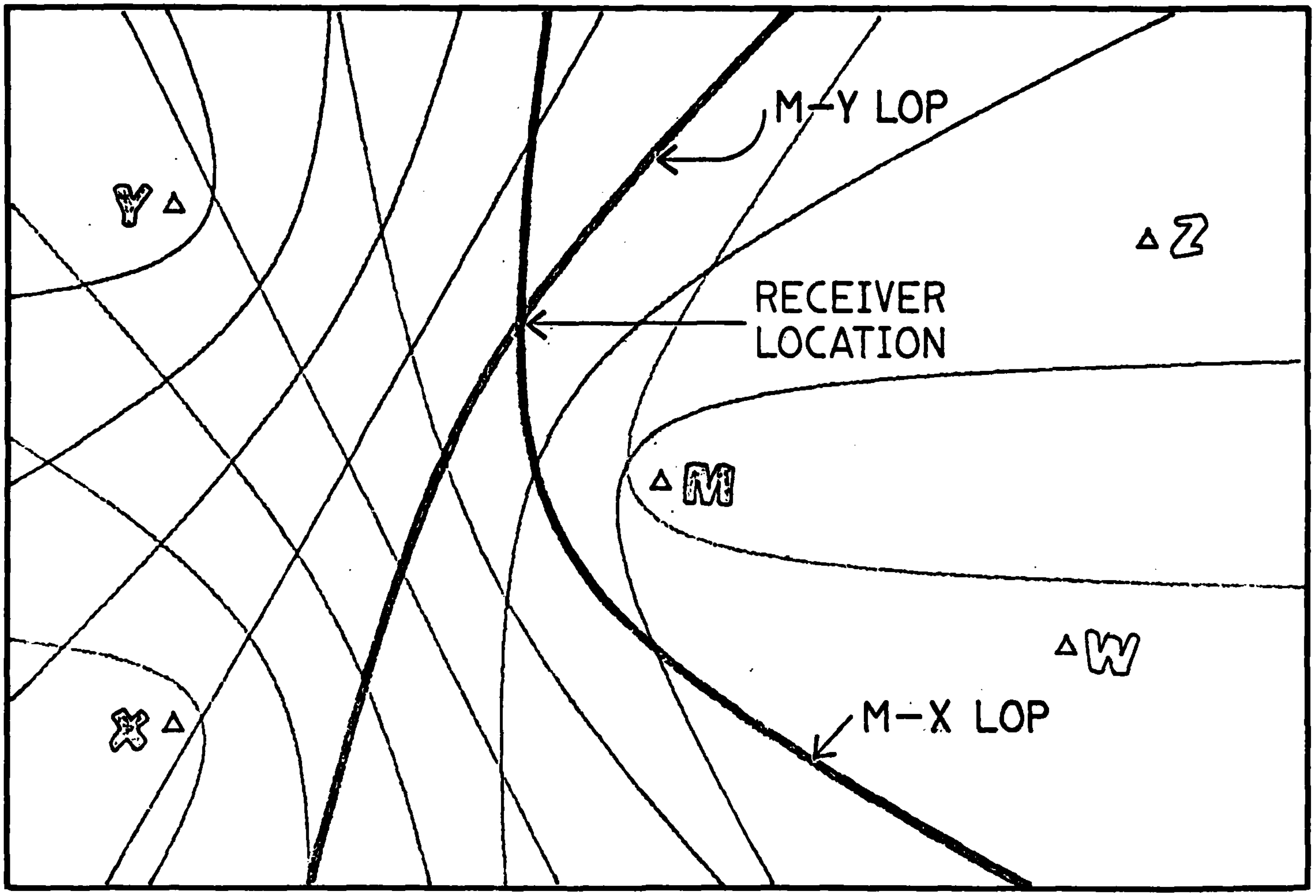


Figure 2.1 Loran-C Position Solution.

The results of the West Coast Loran-C flight test described here will contribute to that assessment through the achievement of these specific test objectives:

- Evaluate the suitability of Loran-C for overland air navigation by quantifying navigation and position accuracy at three selected geographical locations within the chain coverage area of the West Coast Loran-C Chain.
- Test the success of Loran-C as a non-precision approach aid in mountainous areas, using a commercially available Loran-C receiver/navigator as the primary air navigation/guidance system.
- Record the effects of bias shift and station outage on overall accuracy and approach procedures, particularly on or near a baseline extension.
- Calculate the absolute Flight Technical Error (FTE) during Loran-C non-precision approaches using a fixed-wing aircraft typical of general aviation.

2.4 THE U.S. WEST COAST LORAN-C CHAIN

Fallon, Nevada is the site of the master station of the West Coast Loran-C chain. The secondary stations are at George, Washington, Middletown, California, and Searchlight, Nevada (see Figure 2.2). To meet the test objectives, three airports within the chain coverage area were chosen for non-precision test approaches. Each location typified a worst-case set of conditions against which to test the characteristics of Loran-C.

2.5 TEST LOCATIONS

Lake Tahoe Airport at South Lake Tahoe, California was chosen for two reasons. First, the lakeside airfield sits in a mountain-rimmed bowl near the center of the West Coast chain coverage area. Test approaches there would demonstrate the all-terrain characteristics of the Loran signal. Second, the Loran-C approach designed for Lake Tahoe airport, and discussed in Section 4.1, would demonstrate Loran-C accuracy

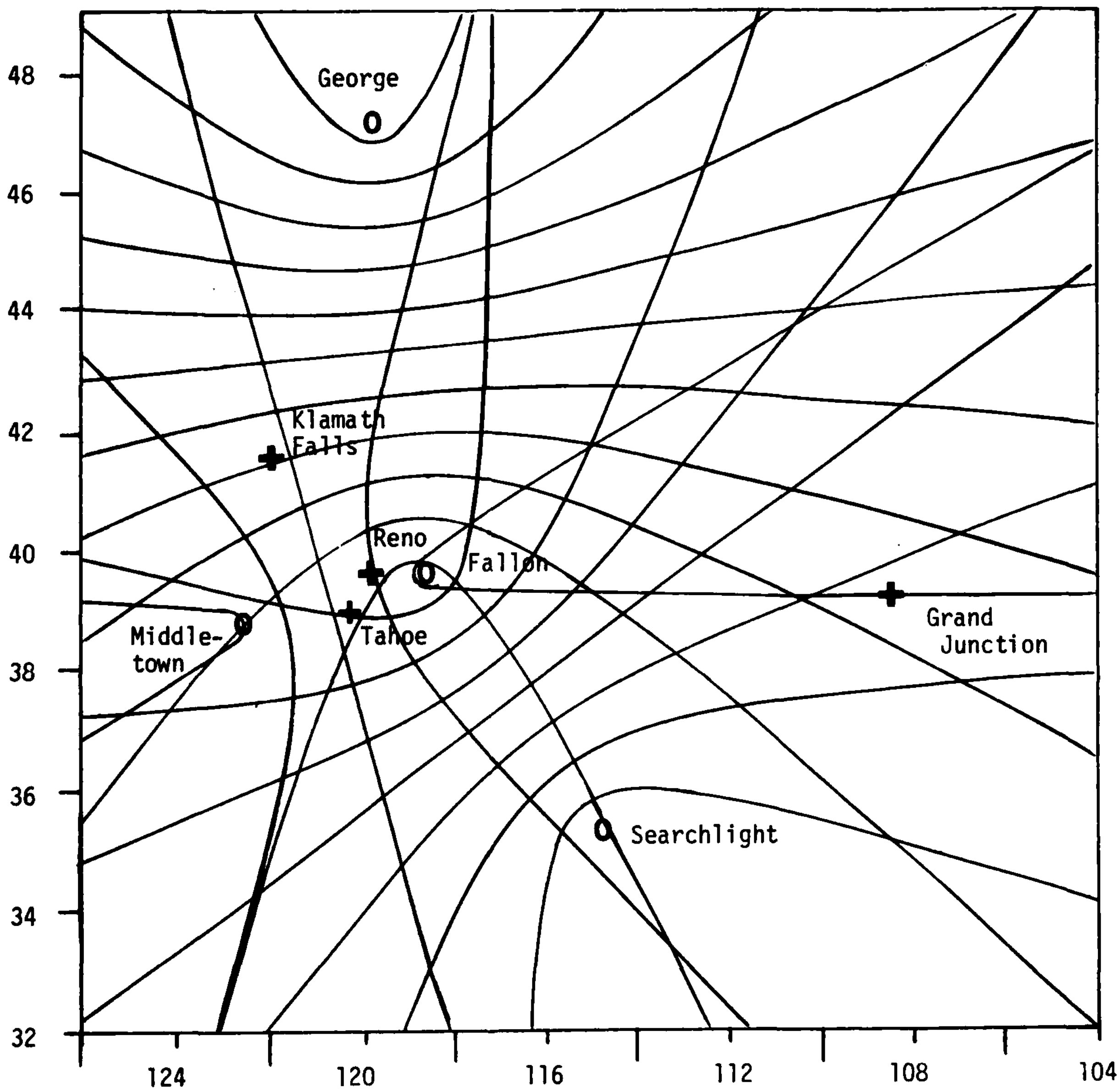


Figure 2.2 West Coast Loran-C Chain and Flight Test Locations

and show that Loran-C could safely be flown to a lower minimum altitude than that of the existing VOR/DME approach because positive, on-centerline course guidance would be possible down to the runway threshold.

Kingsley Field in Klamath Falls, Oregon was selected because it combined mountainous terrain with a location on the Fallon-Searchlight baseline extension. Klamath Falls was a substitute for Bishop Airport in Bishop, California. After system checkout flights began, it was obvious that the mountain wave turbulence likely at Bishop would make the tasks of both the pilots and of the rear-seat observer/technician nearly impossible. The area around Klamath Falls, while not as precipitous, was mountainous enough to further test the all-terrain capability of Loran-C as well as Loran-C performance near the baseline extension.

The selection of Walker Airport, Grand Junction, Colorado was suggested by two factors. First, the surrounding terrain was as mountainous as any in the United States. Second, Grand Junction sat at the eastern-most edge of the West Coast chain coverage area and would test the fringe area characteristics of the Loran-C system. Section 4.0 contains discussion of the existing and planned approaches at all the test locations.

Ground truth data, against which the Loran-C position would be compared for accuracy, was collected using a DME multilateration system called a Remote Area Precision Positioning System, or RAPPS. The system, designed by the Sierra Nevada Corporation of Reno, Nevada, was able to use up to 6 DME beacons to track the aircraft.

The Loran-C receiver/processor, the Remote Area Precision Positioning System (RAPPS), and a module of data collection equipment were co-located in an instrumentation rack constructed by the Sierra Nevada Corporation. The testbed aircraft was first positioned at the Reno/Stead airport for rack installation. Subsequent checkout flights were flown at Reno International Airport and Reno/Stead Airport. The Reno base of operations was also convenient to both the Lake Tahoe and Klamath Falls test locations.

3.0 THE TEST EQUIPMENT AND AIRCREW

This portion of the report concerns itself with the mechanics of testing Loran-C as a non-precision approach aid. It contains a description of the aircraft used, the RNAV/Loran-C receiver/processor, the ground truth and data acquisition systems, and the aircrew.

3.1 AIRCRAFT

For the test, the contractor provided a Piper PA-23-250 Aztec D, tail number N6686Y (see Figure 3.1). The Aztec is a six place light twin with a payload, an interior roominess, a simplicity of systems, and an instrument approach stability that ideally suit it for a test of this kind. The aircraft is unpressurized, and powered by two normally aspirated, fuel-injected internal combusion engines.

To accommodate a rack containing the ground truth and data acquisition systems and the Loran-C receiver, the middle two seats were removed, leaving the two front seats for the pilot and copilot/safety observer and the rear bench seat for the observer/technician who operated and monitored the ground truth system and data acquisition equipment.

Typical of general aviation light twin aircraft, the primary flight and navigation instruments are located on the pilot's instrument panel. The power instruments and fuel gauges are on the copilot's panel. The center panel contains radios — both Comm. and Nav. For the test, a Loran-C course deviation indicator (CDI) was placed at midpoint on the center panel, with a Comm/Nav radio above and below (see Figure 3.2), to separate it from the CDIs for the VOR and ILS receivers located on the pilot's instrument panel. Next to the Loran CDI was the frequency selector for the Distance Measuring Equipment (DME). The DME display head was relocated below the copilot's panel to the right of the yoke.

Due to space limitations, the Loran-C control display unit (CDU) could not be panel-mounted. It was placed in a special receptacle on the front surface of the copilot's seat with the control head facing upward so that it could be easily seen and operated by the copilot. In that position, however, the CDU was not within the pilot's field of view.

Figure 3.1 Flight Test Aircraft, N6686Y

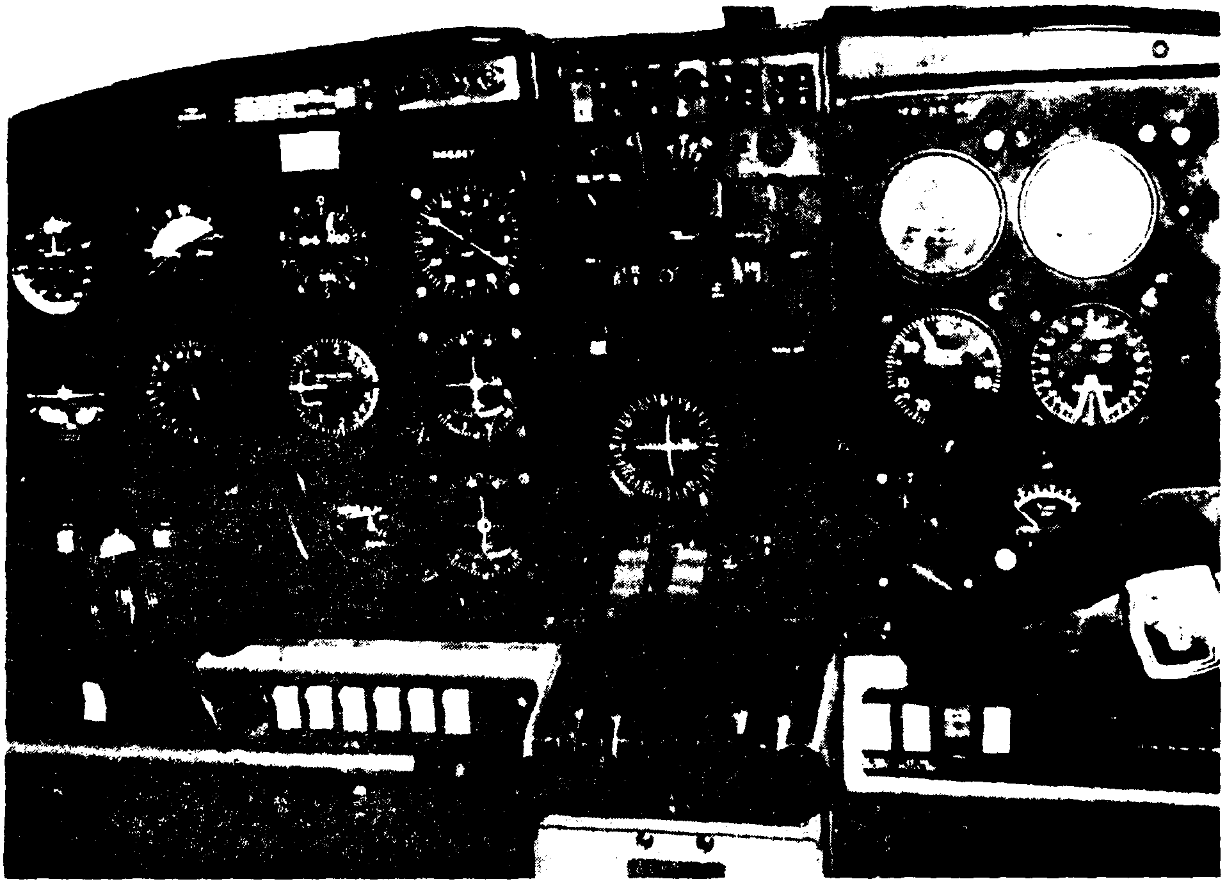


Figure 3.2   Loran-C CDI

3.2 LORAN-C RECEIVER/PROCESSOR

The RNAV/Loran-C airborne equipment used for the approach testing was a Teledyne TDL-711 micro-navigator system consisting of an E-field vertical antenna mounted on top the aircraft above the copilot's station, a receiver/computer unit mounted on the data acquisition rack, a control display unit mounted face-up on the front surface of the copilot's seat, and a course deviation indicator installed in the center instrument panel to display Loran-C course deviation.

The control display unit is the operator's interface with the Loran-C system. It displays position information both in latitude/ longitude and time differences; shows which waypoint, or waypoint pair, has been selected; displays all navigation and test modes; and, shows the information being entered through the keyboard.

There are six decimal points for use with the data shown in each upper display window (two of the six in each are shown in Figure 3.3). These same decimal points are also used to warn the crew of non-standard Loran-C system operation. All the decimal points blink when the processor is operating in the master independent mode (the master signal is unusable or non-existent and a third secondary has been added to the computations, with one of the secondaries selected as master). They remain on steady when navigation information (and thus, the computed position) is unusable.

The rotary data selector switch chooses the information to be displayed:

- "WAYPT": the selected waypoint position is displayed, or the coordinates to be entered for the selected waypoint are shown
- "PRES POS": position displays present position or allows entry of present position.
- "DIST/BRG": displays in the left and right windows, range and bearing to the selected "TO" waypoint in the "FROM-TO" window
- "ETE/GS": the processor shows time to go to the "TO" waypoint and present ground speed

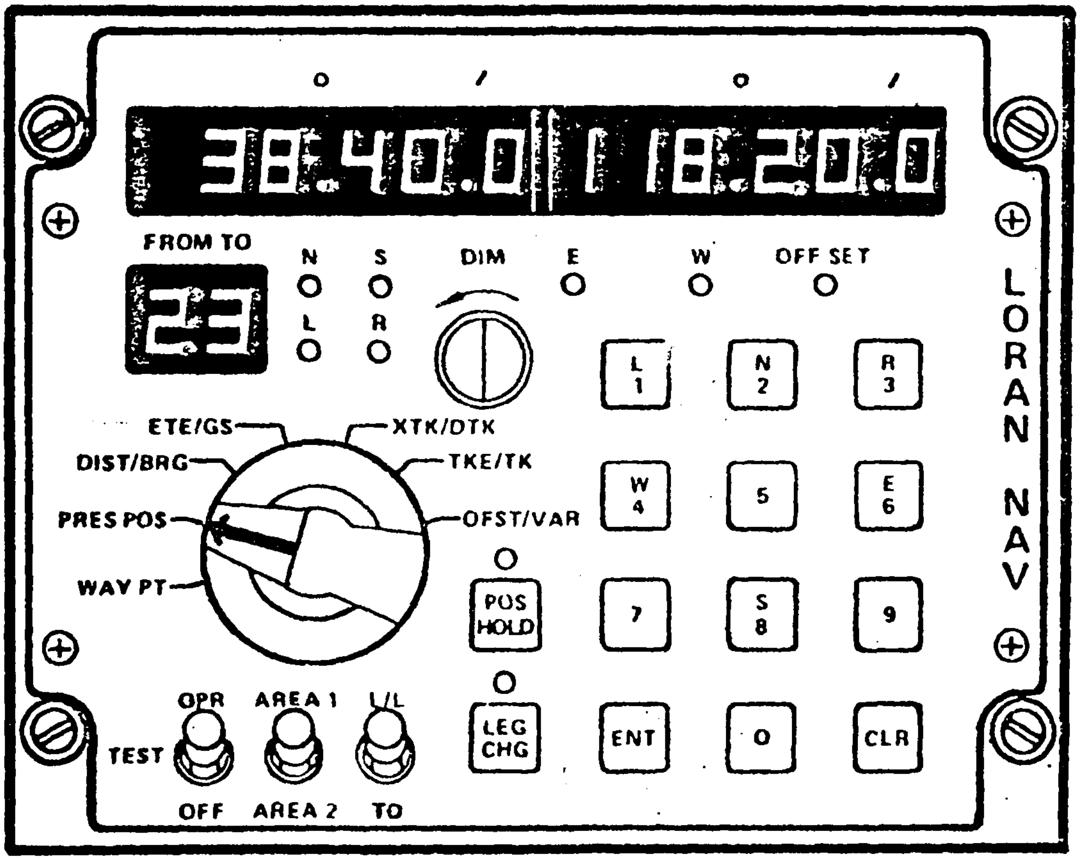


Figure 3.3 TDL-711 Control Display Unit

- "XTK/DTK": shows cross track distance on the left and desired track angle on the right
- "TKE/TK": displays track angle error and track angle
- "OFST/VAR": shows the current parallel offset distance (or allows selection of a new offset), and lets the operator either see the current magnetic variation, if any, or enter a new variation.

The "MODE SELECTOR", (lower left corner) is a three position switch which, at the operator's discretion, either shuts off power to the system, initiates the self-test sequence, or puts the system into normal operation.

One of two pre-programmed coverage areas can be chosen with the area switch. This switch selects the triad (a three-station set of master and secondaries) which is to be used for position computation and navigation. Interchangeable chips of Programmable Read Only Memory (PROM) for all present coverage areas are available from the receiver manufacturer. The "L/L-TD" switch chooses the mode of the selected position display or entry — latitude/longitude or time differences.

Pressing the "POS HOLD" switch stores the aircraft's present position at the moment it is depressed. If the rotary data selector is in the "PRES POS" mode, the displays will freeze. In any event, position continues to be updated once per second. The indicator light stays on until the switch is pressed a second time.

To effect a leg change, the "LEG CHG" switch is depressed and the next waypoint pair is entered using the keyboard. On the TDL-711, the leg change light will flash when the "TO" waypoint has been reached, and the new waypoint "FROM-TO" pair must be entered manually. There is no automatic leg change function. The new waypoint pair appears in the "FROM-TO" window.

The keyboard is for information entry. Certain keys have double functions depending on the position of the rotary data selector switch. The "ENT" key inserts the keyboard entry into the processor. The "CLR" key is used to clear keyboard entry errors.

The "N" and "S" lights indicate latitude, and the "E" and "W" longitude. Whenever an offset course has been entered, the "OFFSET" light remains on.

When the aircraft is left or right of desired track, when the track angle error is left or right of desired track heading, or when the offset course is left or right of nominal, the "L" or "R" lights will be on to show the direction of displacement.

The "DIM" control regulates all CDU lights except the "OFFSET", "LEG CHG", and "POS HOLD" indicators. They are controlled with the cockpit dimmer controls.

Certain internal diagnostic functions can be summoned with coded key entry sequences. Their function will be discussed in Section 6.2.

The output of the Loran-C micro-navigator drives a CDI, giving linear deviation from the selected "TO" waypoint course. Full scale deflection left or right of center is 1¼ nautical miles. The "TO" flag indicates that the aircraft is located short of the "TO" waypoint. The "FROM" flag indicates a position beyond the "TO" waypoint. The red "NAV" flag indicates that steering commands are invalid.

The Loran-C receiver is designed to run a remote display unit (RDU), and the information it provides to that remote display can be externally programmed through the PROM.

3.3 DATA ACQUISITION SYSTEM

Four interrelated elements made up the data acquisition package for the flight test:

1) A Loran-C data subsystem
2) A ground truth data subsystem
3) A real-time data subsystem
4) A data recording subsystem

3.3.1 Loran-C Data Acquisition

The Loran-C receiver outputs primary inflight CDU and RDU data in a serial digital data stream, transmitted once per second. The parameters extracted from that data stream for this test were: time differences, latitude/longitude, cross track deviation, distance to waypoint, waypoint or waypoint pair in use, Loran stations being tracked, Loran stations in

blink status (signal problem noted at transmitter), signal to noise ratios, envelope numbers, offset and/or magnetic variation in use, and the Loran-C triad in use.

The data stream was sent through a serial telecommunications port to an Intel SBC-80 microcomputer which formatted the data and made it available to the data recording subsystem.

3.3.2 Ground Truth Data Acquisition

The Remote Area Precision Positioning System (RAPPS), see Figure 3.4, was the heart of the ground truth package. Operating at standard L-Band TACAN frequencies and fully compatible with existing TACAN and DME installations, the RAPPS used precision multilateration to track the test aircraft.

The system interrogator was a standard King KDM 7000 DME set compatible with ARINC characteristic 586. However, in place of a standard channel selector the RAPPS system used a special purpose indexing frequency selector which allowed the selection of up to six DME frequencies. It cycled through those frequencies, pausing 1.0 second on each for range data, which was then passed to the Intel SBC-80 microcomputer.

One additional input from a Narco AR-500 digital encoding altimeter was necessary because the measured DME slant range had to be converted to ground ranges before the multilateration problem could be solved.

Additional portable transponder beacons were used for the test since dual beacon Rho-Rho tracking geometry requires that certain angular relationships exist throughout the approach. Figure 3.5 shows the relationship between the amount of error and the crossing angle of lines of position from multiple beacons. At a 90° crossing angle position error is reduced to its lowest level, doubling as the crossing angle shallows to 30°, and proceeding to indeterminacy as the angle shallows further.

The implications of such angular restraints are illustrated in Figure 3.6, showing beacon placement at Lake Tahoe. LTA is the Lake Tahoe VORTAC, MKB is a portable DME beacon at Meeks Bay, and LTT is another portable beacon on the airport at Lake Tahoe. The LTT/MKB baseline is shown as the straight-line between the Lake Tahoe VORTAC

Figure 3.4 [illegible] (arrow)

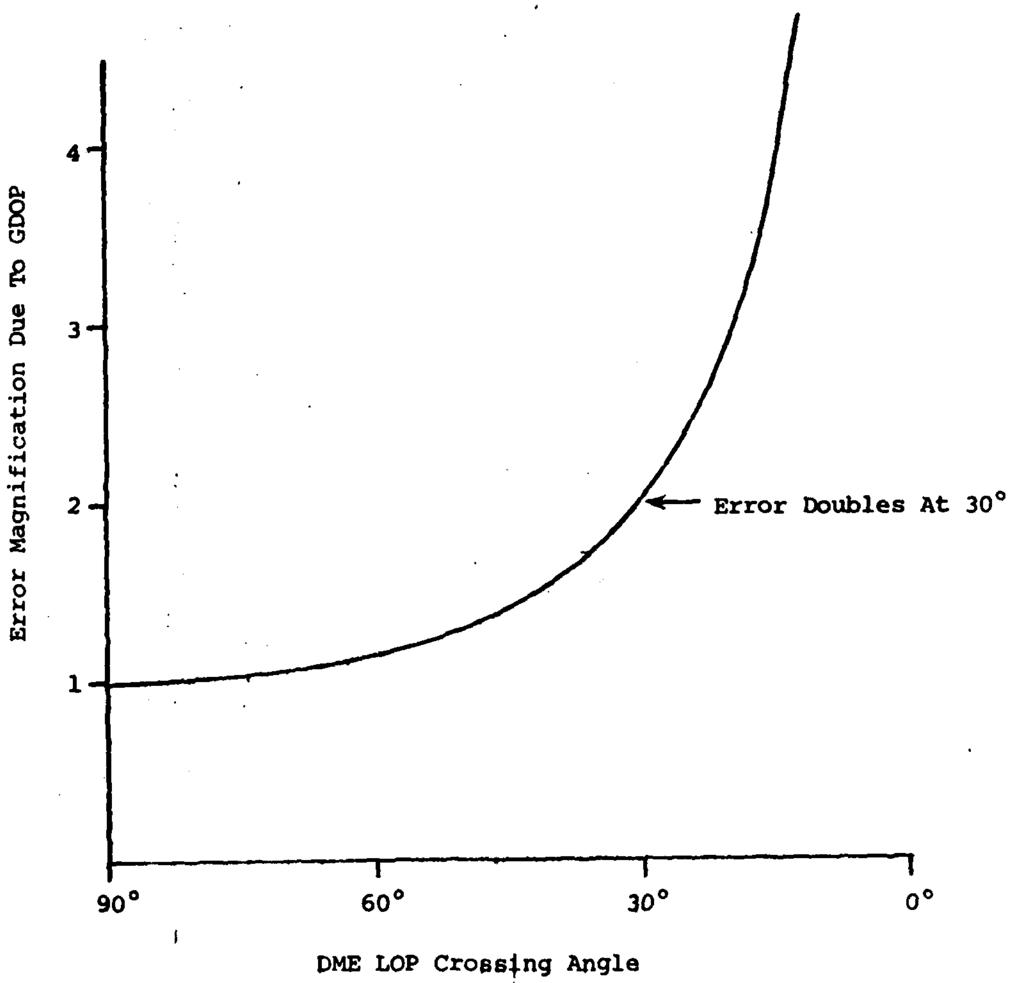


Figure 3.5 Relationship of Crossing Angle To Error Magnification

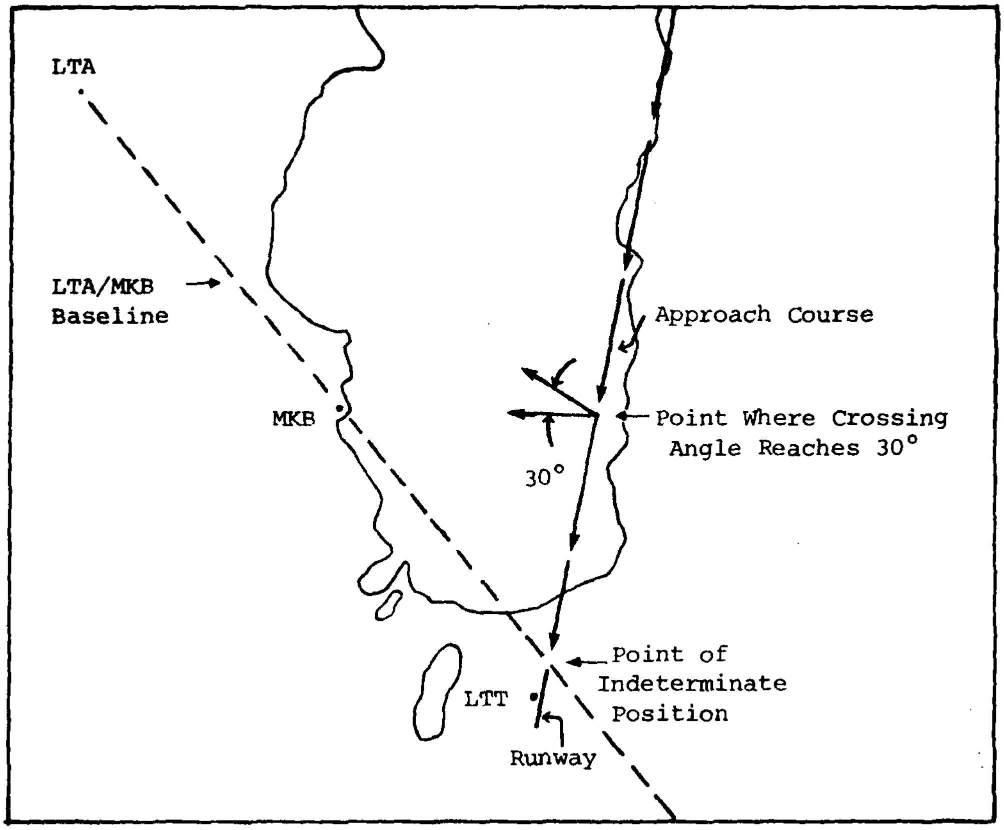


Figure 3.6   Beacon Geometry At South Lake Tahoe

and the Meeks Bay portable. The figure shows how the relationship between the angle to the aircraft (at the apex of the triangle) from both the LTA and MKB beacons changes as the aircraft gets closer to the airport on the approach course. At points closer to the airport than abeam the MKB beacon, the crossing angles begin to drop below 30° and errors inflate. At this point, however, the angular relationship is good between MKB and LTT. As the aircraft nears the airport this relationship, too, begins to deteriorate until a point just off the runway when all three beacons are in a straight line and the aircraft position cannot be determined. If the aircraft were seen as the apex of the angle, the angular difference between the two beacons should be at least 30° but not more than 150°. The beacons, then, should neither both be on or near the approach centerline, nor both be placed on the airport. These geometry considerations coupled with the line-of-sight constraints of beacon transmissions figured significantly in the choice of test airports. The final choices were the best mix of existing beacons (TACAN and DME) and suitable locations for portable beacons, the latitude and longitude of which could be precisely enough computed to preserve the high standard of accuracy required for experimental testing. The portable beacons used were the Butler Model DME 1020 and the Vega Model 316-L, both of which, depending on the use of appropriate converters, used either AC or DC line power.

In general, existing operational DME transmitters were preferred, assuming the above mentioned geometry and terrain constraints were met. The next preference was portable beacon placement within the subject airport boundaries. Finally, when constraints dictated it, remote sites were investigated using U.S. Geological Survey Quadrangle Maps. Decision in favor of a remote site depended on the availability of surveyed bench markers, tracking geometry, and site accessability. The locations of the remote beacons used in the test are discussed in Section 4.0.

3.3.3 Real-Time Data Presentation

A Tektronix 4051 intelligent graphics terminal provided the real-time data entry and operator control capability. Ground truth data and Loran-C receiver data were passed to the 4051 by the Intel SBC-80 microcomputer. The real-time system computed aircraft position every 6 seconds using

the RAPPS data and maintained a continuous CRT plot of intended position. The plot was available to the technician/observer during flight as it happened.

3.3.4 Data Recording

A Tandberg Model SCDR-3000 recorder, connected to a serial telecommunications port on the Intel SBC-80, put the ground truth and Loran-C data streams onto digital data cartridge tape for post flight data reduction and analysis.

3.3.5 Data Acquisition Equipment Rack

The data acquisition equipment rack (see Figure 3.7) stood in place of the two middle seats in the test aircraft, facing rearward toward the system technician/observer. Installed on the rack were:

- 60 Hz power inverter
- Blind encoding altimeter
- DME, and DME channel programmer
- Intel SBC-80 computer
- Tektronix 4051 intelligent terminal
- Tandberg SCDR-3000 digital cartridge recorder
- Instrumentation clock

Special purpose hardware which plugged into the computer bus was constructed to interface the Loran-C receiver and the RAPPS DME system to the computer.

There were three components external to the rack — an E-field Loran-C antenna on top of the aircraft over the copilot, and two DME antennas, one on top the aircraft and one on the belly. DME antenna switching was manually controlled by the technician/observer. Figure 3.8 shows the E-field Loran antenna and, aft of that, the short, rod-like topside DME antenna.

3.4 AIRCREW

Two instrument rated contractor pilots flew the test profiles.

The technique used during the test approaches was dictated both by mission requirements and by the physical placement of the Loran-C CDU. The pilot flew the approach "under the hood" to simulate IFR conditions, using the Loran-C CDI for guidance. The copilot/safety observer operated

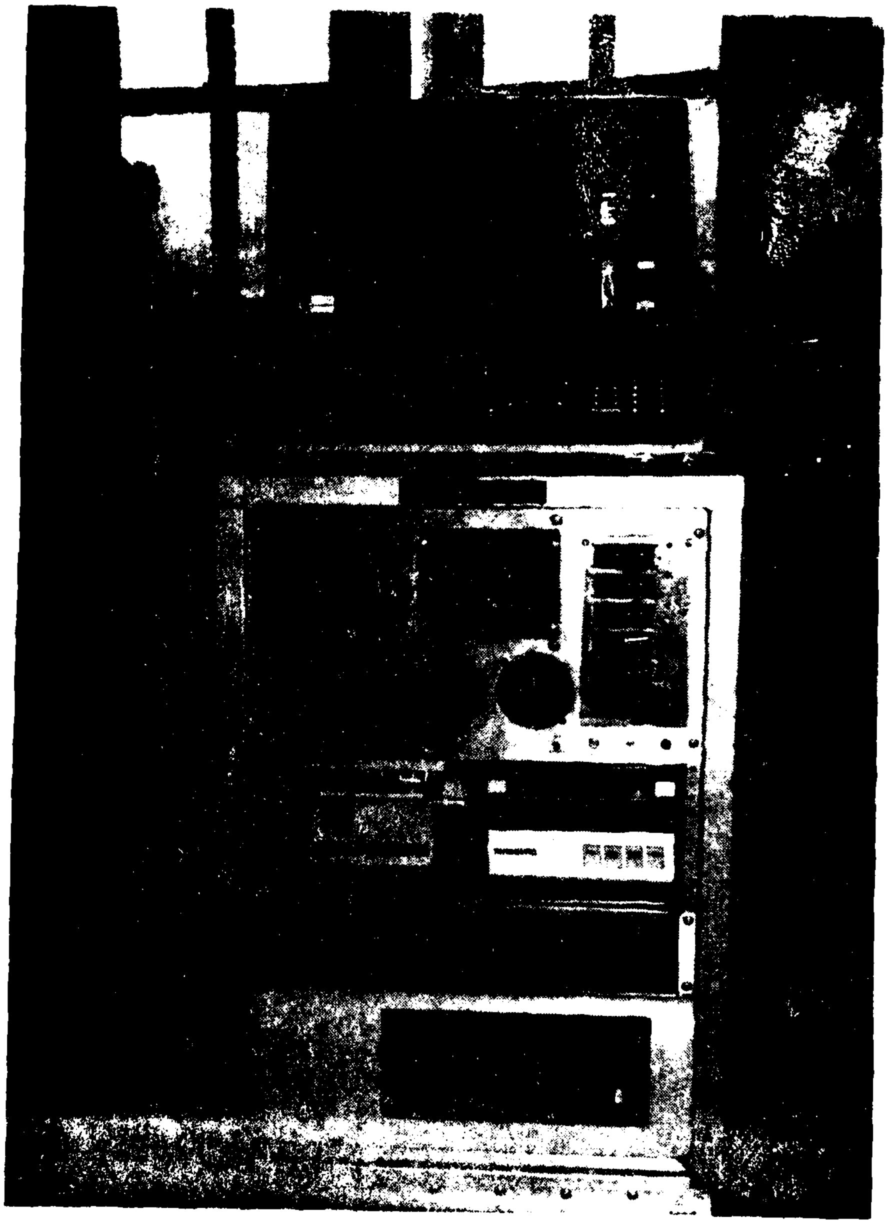


Figure 3.7 Data Acquisition Rack

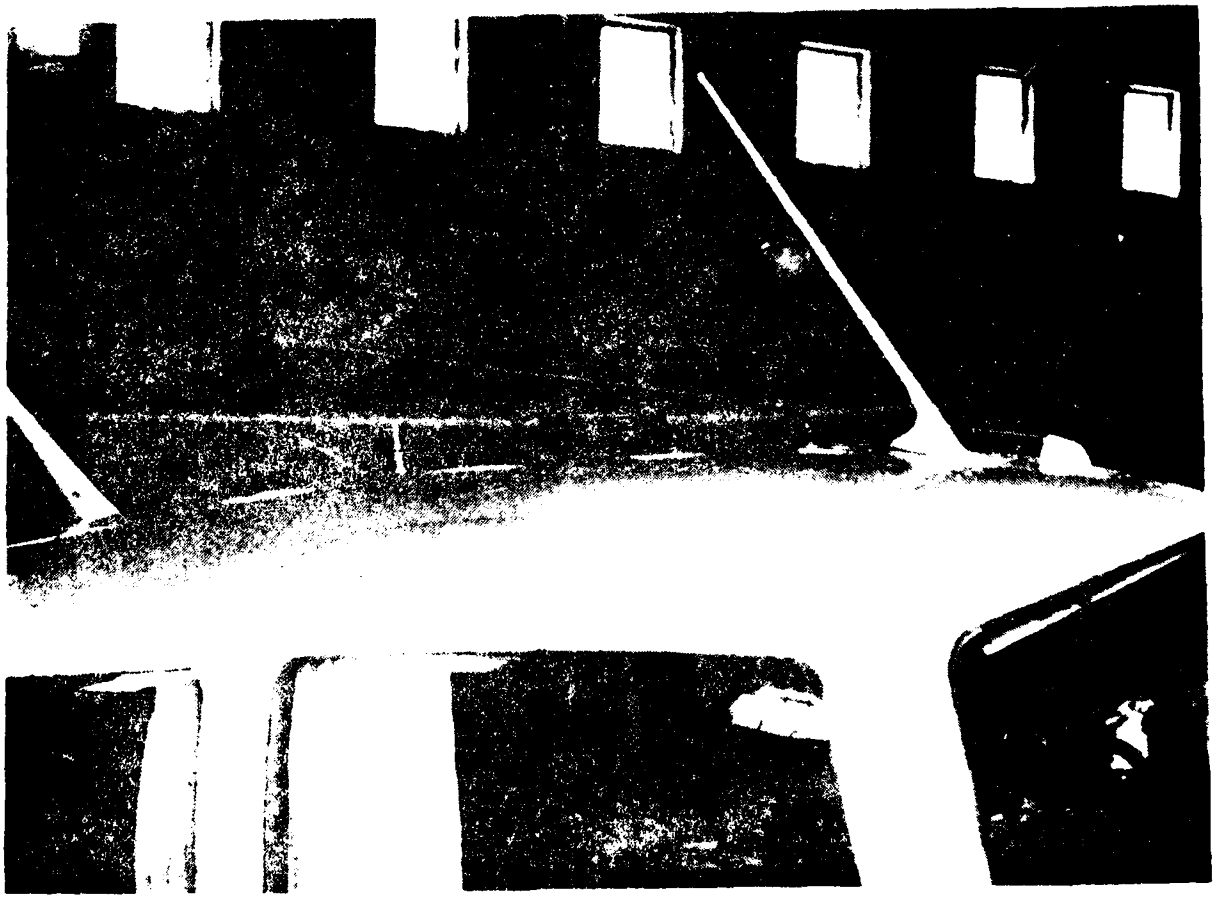


Figure 3.8 E-Field Loran Antenna and Topside DME Antenna

the Loran-C CDU, advised the pilot of distance to waypoint, and kept continuous watch for conflicting terrain and/or air traffic. The copilot also made all radio transmissions and kept a log of significant events during each approach. The pilot remained "hooded" until reaching the missed approach point. The "hood" was repositioned prior to intercepting the inbound approach course for the next approach.

Figure 3.9 shows the approach log used by the copilot/observer for each approach. The log served to record pilot blunders, Loran-C operational performance, ATC deviations, CDU indications, or other malfunctions. The logs were used, when necessary, to outline the conditions under which each approach was flown and to corroborate events and data.

The technician/observer who monitored the data acquisition equipment was an employee of the Sierra Nevada Corporation.

LORAN-C OBSERVER LOG   AREA CAL: YES NO

DATE:______________________ OBSERVER:________________ FLT#/APPR#: ____/____

PILOT:______________________ LOCATION:________________ TRIAD:______________

WP SEQ	SNR	TRIAD SWITCH TIME	BLINK CEASE TIME	COMMENTS

Figure 3.9 Observer Log

4.0 FLIGHT TEST PROFILES

This section is a description of the three Loran-C flight test profiles and two system checkout profiles and contains a chronology of the flight test.

4.1 SOUTH LAKE TAHOE, CALIFORNIA

The selection of Lake Tahoe Airport for Loran-C flight testing rose out of a number of factors. First, the airport was convenient to Reno, Nevada where the data recording and ground truth systems were constructed and installed in the test aircraft. Second, the existing approach, a VOR/DME circling procedure, using the Lake Tahoe VORTAC (LTA), has an offset final approach segment, a missed approach point 4.2 nm from the threshold, and a minimum descent altitude 2536 feet above ground level. Third, the Loran-C approach could be designed as a straight-in to a considerably lower minimum descent altitude. Last, the lake and the airport are surrounded by mountainous terrain (the minimum sector altitude is 11,900 feet mean sea level), which provided a realistic test of the suitability of the Loran signal in such topography.

The existing approach, the VOR/DME-A circling to runway 18, is summarized in Figure 4.1. The relatively high MDA is forced by line-of-sight constraints on the VOR and DME signals.

The Loran-C test approach, on the other hand, was designed to be more straightforward (see Figure 4.2). It contained six waypoints, the first four defining the final approach course, the last two the missed approach holding procedure (a duplicate of the VOR/DME-A missed approach procedure).

Waypoint 1, the initial approach fix (IAF), was 15 nm from the threshold. The entry altitude proposed by the test plan was 11,000 feet MSL, but actual conditions showed that an entry altitude of 8500 feet MSL was sufficient for safety and avoided large altitude changes during the ensuing portions of the procedure.

Waypoint 2, the intermediate fix (IF), was 10 nm out from the runway threshold. The minimum altitude was 7500 feet between waypoint 2 and waypoint 3, the final approach fix (FAF). Descent was permitted to no lower than 6900 feet between waypoint 3 and waypoint 4, the Missed

SOUTH LAKE TAHOE, CALIFORNIA

LAKE TAHOE - VOR DME-A RWY 18

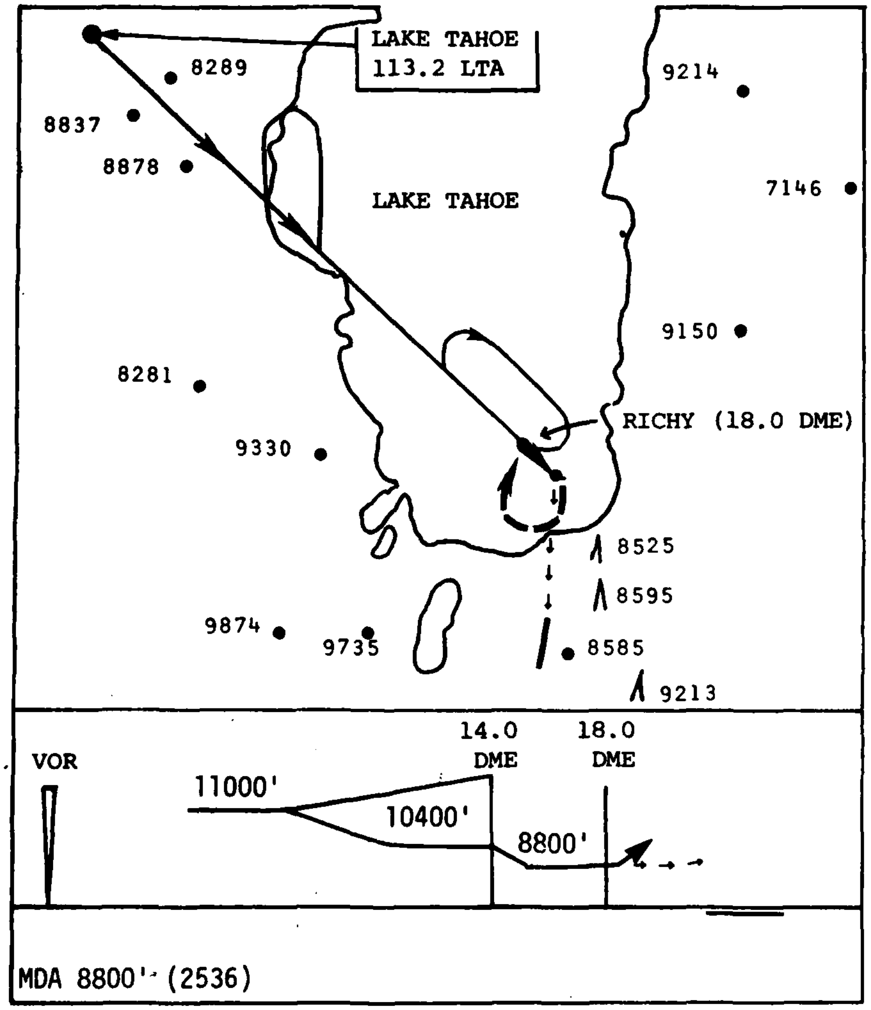


Figure 4.1 Existing VOR Approach At South Lake Tahoe, Cal.

SOUTH LAKE TAHOE, CALIFORNIA

LAKE TAHOE - RNAV/LORAN-C RWY 18

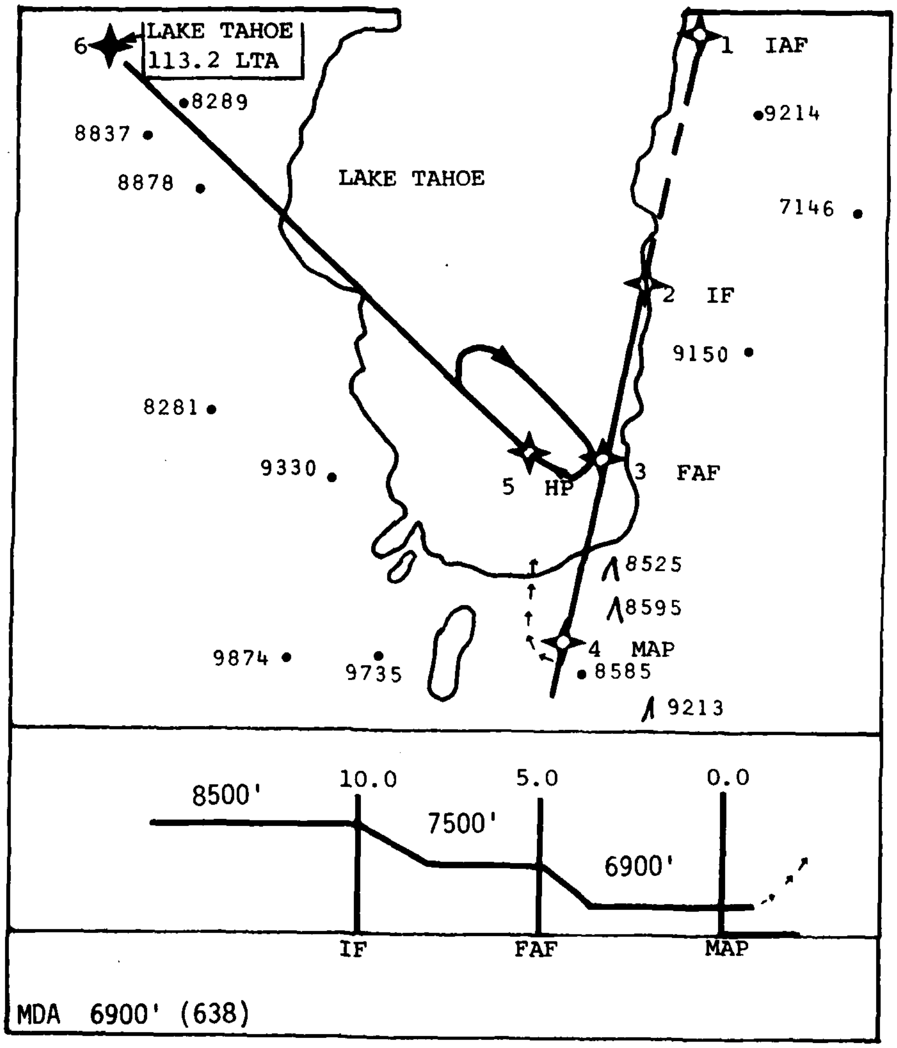


Figure 4.2 Loran-C Test Approach

Approach Point (MAP). Descent was planned to an MDA of 6900 feet MSL (600 feet AGL).

The missed approach was a climbing right turn direct to waypoint 5, with a right hand holding pattern at 8500 feet. The missed approach holding procedure was not flown during the test.

The Lake Tahoe approaches were attempted on 7 July 1979, but were cut short, after two "un-hooded" checkout approaches, when an aircraft electrical system malfunction shut down the data acquisition equipment and forced the tests to be terminated.

The Tahoe approaches were successfully flown on 26 July 1979. The Fallon-Middletown-Searchlight (FMS) and Fallon-Middletown-George (FMG) triads (see Figure 4.3) were preprogrammed in the Loran-C TDL-711 microprocessor, to be selected by the area 1 - area 2 switch on the CDU.

Portable beacons for the ground truth tracking system were used along with the Lake Tahoe VORTAC DME. One portable beacon was installed on the airport itself, on the north approach side of the tower. Another was placed at a high, roadside location overlooking Meeks Bay on the western shore of the lake. The Reno VORTAC was used as an additional tracking source, but the high terrain at lake's edge made it useful only during the initial portion of the procedure.

Table 4.1 outlines the proposed and accomplished approaches at each of the test locations.

4.2 KLAMATH FALLS, OREGON

Test approaches at Klamath Falls were substituted for those at Bishop, California when it was determined that the mountain wave turbulence likely at Bishop would severely degrade the comfort and efficiency of the rear-seat technician/observer. Klamath is also in mountainous terrain, though not as precipitously mountainous as Bishop, and sits near the Fallon-Searchlight baseline extension. As such, it offered an excellent set of test conditions: Topography varied enough to show the low altitude signal characteristics of Loran-C, and location on a baseline extension tested both the signal propagation characteristics and bias shift and the receiver/processor's ability to function under conditions of poor geometry.

Table 4.1 PROPOSED AND ACTUAL WEST COAST LORAN-C FLIGHT TEST MISSIONS

		NUMBER OF APPROACHES BY LOCATION											
		LAKE TAHOE				KLAMATH FALLS				GRAND JUNCTION			
		PROPOSED		ACTUAL		PROPOSED		ACTUAL		PROPOSED		ACTUAL	
FLIGHT	PILOT	FMS	FMG	FMS	FMG	FMS	FMG	FMS	FMG	FGS	FMG	FGS	FMG
1 C/O	R	1	1	1	1								
2 C/O	S					1	1	NO LOCK	2				
3	S					3	2	NO LOCK	3				
4	R					2	3	NO LOCK	3				
5	R	3	2	3	2								
6	S	2	3	2	3								
7 C/O	R									1	1	1	1
8	R									3	2	NO LOCK	1
9	S									2	3	NO LOCK	NO LOCK
TOTAL		6	6	6	6	6	6	0	8	6	6	1	2

Total Proposed = 36
Total Flown = 23

F = Fallon (Master)
G = George
M = Middletown
S = Searchlight
C/O = Checkout
Pilot R = Richardson
Pilot S = Scalise

/NOTE:/ Data was collected at Reno International and Reno/Stead. 3 visual approaches were flown at Reno International and 2 tracking passes were made at Reno/Stead.

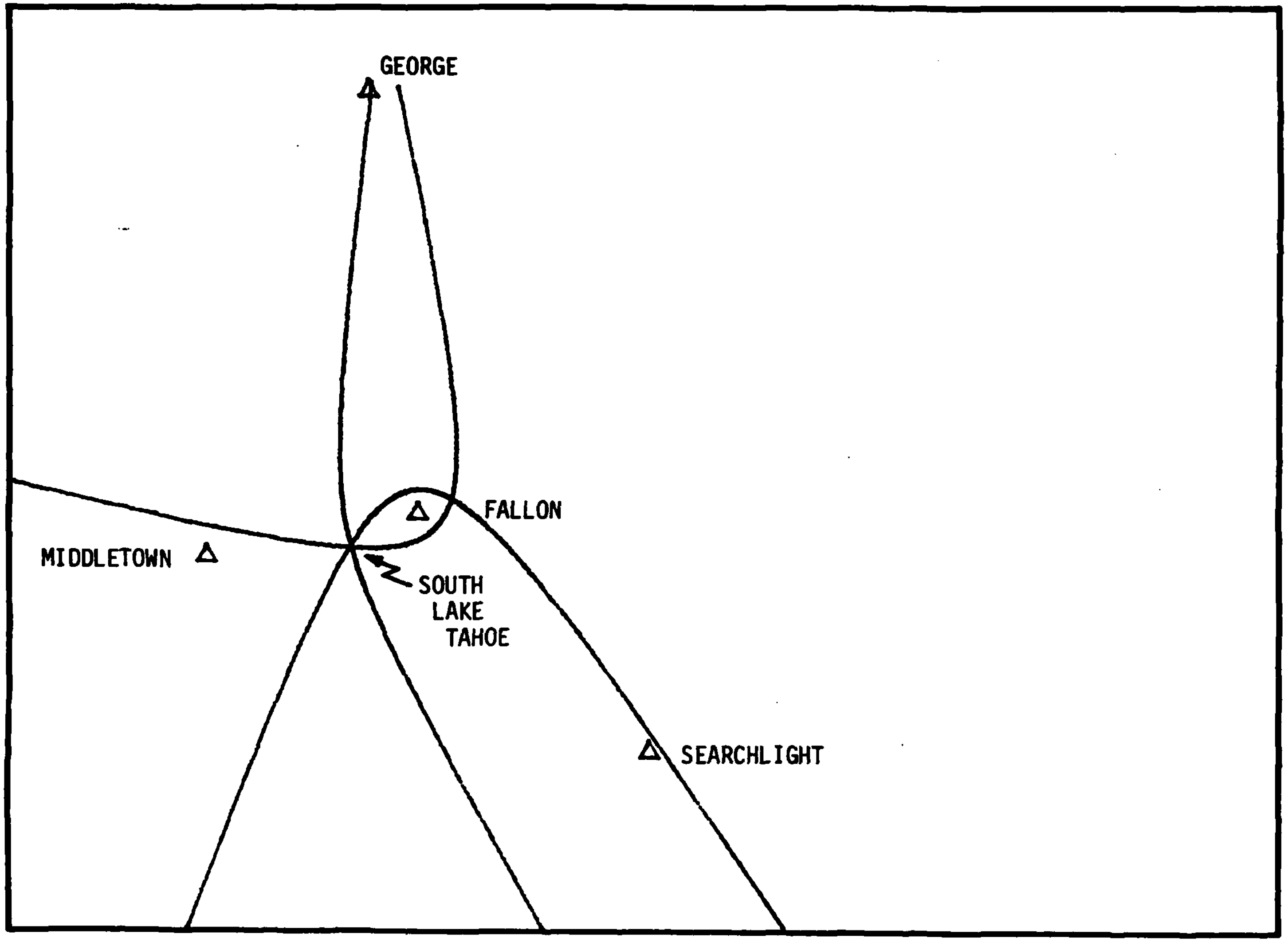


Figure 4.3 West Coast Loran-C Chain Geometry At South Lake Tahoe

The existing primary approach to Kingsley Field, Klamath Falls, Oregon is an ILS to runway 32 (Figure 4.4). The Loran-C approach was designed to coincide as much as possible with the ILS to assure terrain clearance and create a minimum traffic interruption (Figure 4.5). Including the IAF waypoint 15 nm out, the Loran approach had four waypoints, arranged straight-in. Waypoint 2 was the IF (minimum altitude to the IF was 7100 feet MSL). Waypoint 3 was the final approach fix (6200 feet MSL minimum descent between 2 and 3), and, waypoint 4 was the MAP. Minimum descent altitude was 4820 feet (730 feet AGL).

Two portable beacons and the Klamath Falls DME were used for ground tracking during the Klamath flight test. One beacon was installed on a privately owned farm west of the final approach course. The other was located near an antenna farm on Stukel Mountain, east of the final course.

The planned number of approaches could not be flown, however, because no lock-on was possible using the Fallon-Middletown-Searchlight triad. The reasons for this failure to track are discussed in Section 6.0, and the proximity of Klamath Falls to the Fallon-Searchlight baseline extension can be seen in Figure 4.6.

Twelve approaches had been proposed, including 2 checkout approaches. Eight (8) were flown, 2 checkout approaches and 6 data approaches (3 by each pilot). The Fallon-Middletown-George triad was used. The Klamath Falls test flights took place on 24 and 25 July 1979.

The Klamath approaches, proposed and accomplished, are shown in Table 4.1.

4.3 GRAND JUNCTION, COLORADO

Walker Field at Grand Junction, Colorado offered the opportunity to test two important aspects of Loran-C — poor LOP geometry (because Walker is near the Fallon-Middletown baseline extension), and fringe area coverage (because Walker is 500 nm east of the Fallon master and 700 nm southeast of the George secondary).

The primary instrument approach (Figure 4.7) at Grand Junction is an ILS to runway 11. Entry altitude in 7900 feet and glideslope intercept should take place over the Fruita NDB (8.9 nm from the threshold at 7600 feet.

KLAMATH FALLS, OREGON

KINGSLEY - ILS RWY 32

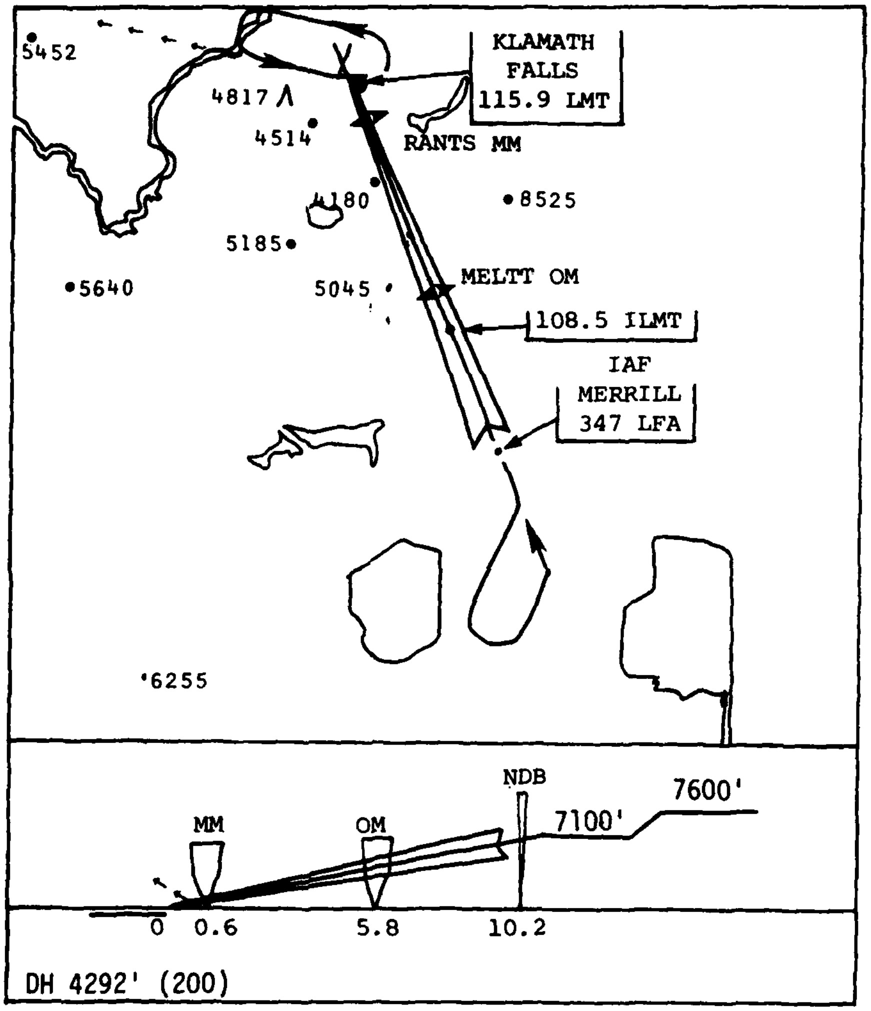


Figure 4.4 Existing ILS Approach At Klamath Falls, Ore.

KLAMATH FALLS, OREGON

KINGSLEY - RNAV/LORAN-C RWY 32

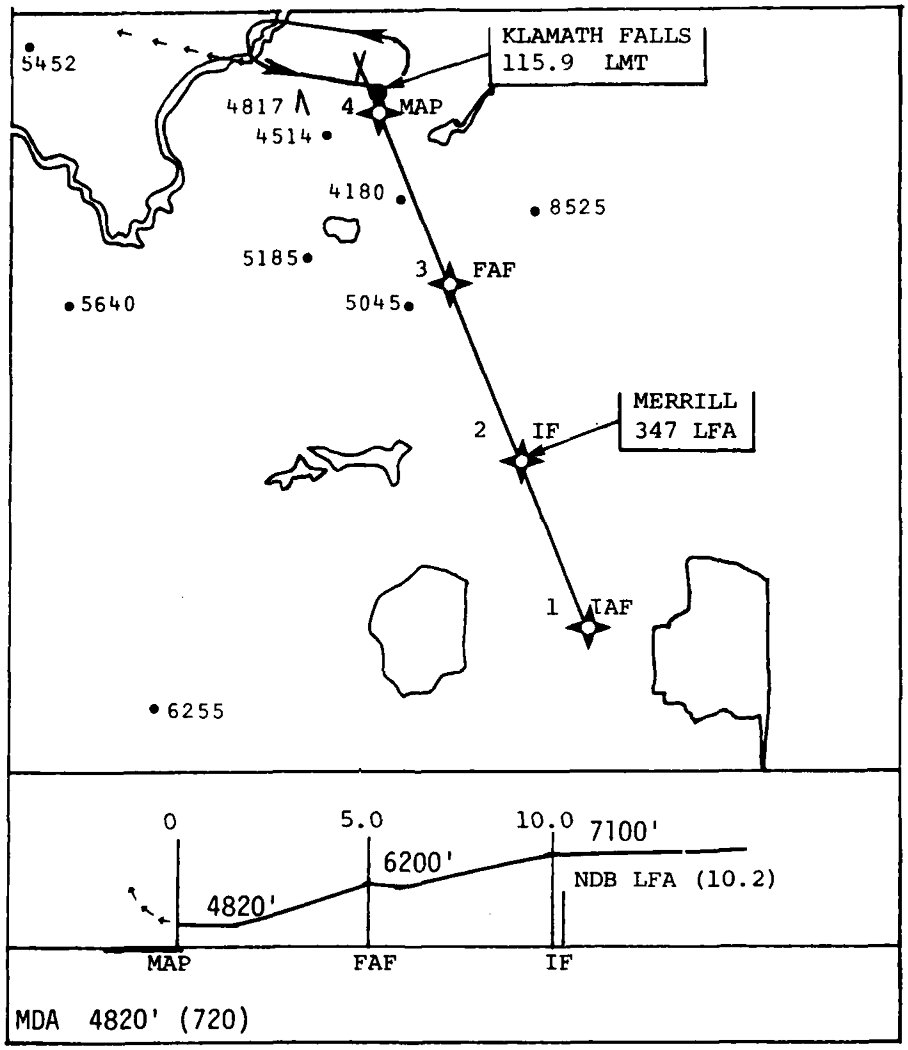


Figure 4.5 Loran-C Test Approach

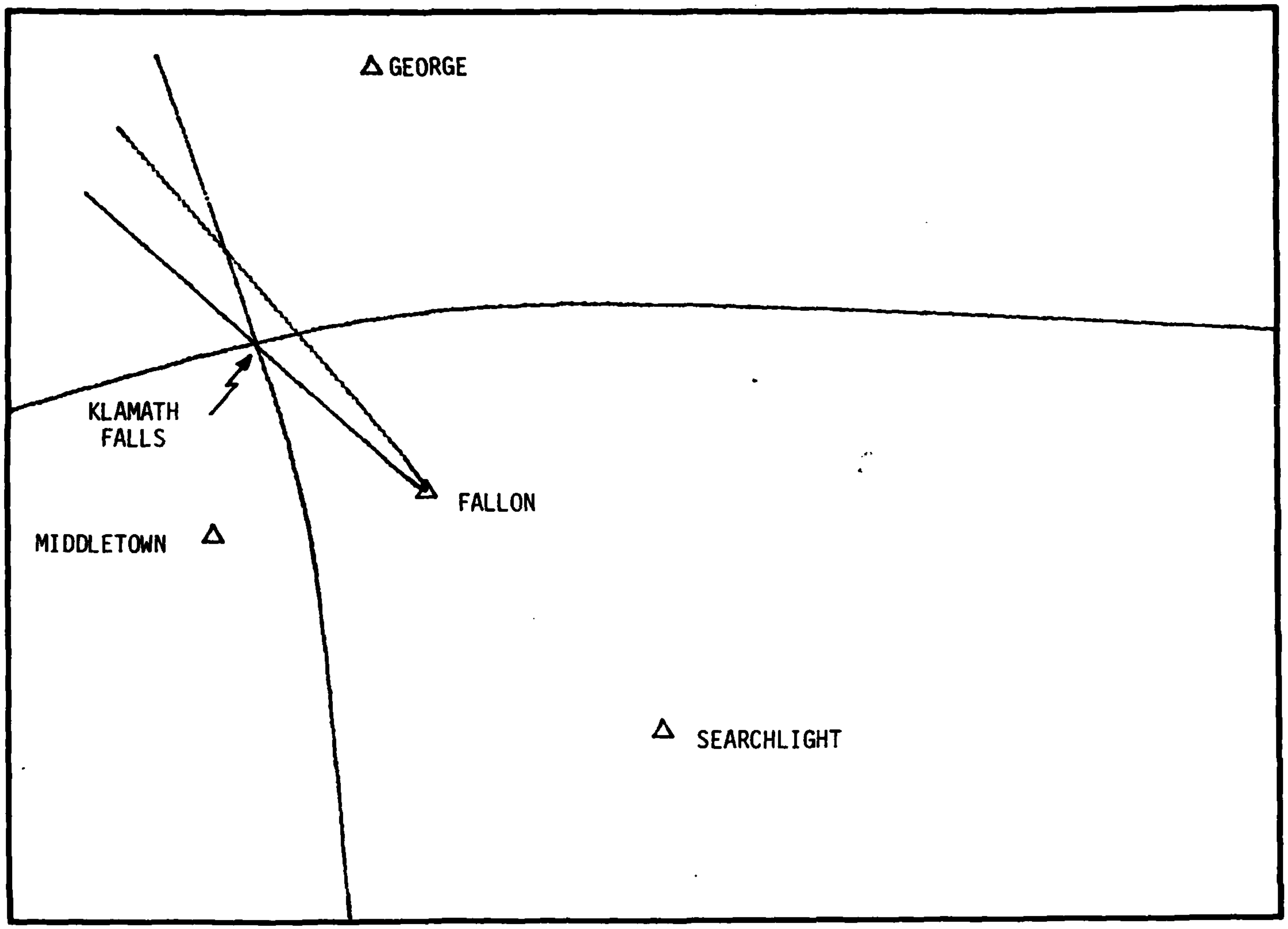


Figure 4.6 West Coast Loran-C Chain Geometry At Klamath Falls, Ore.

GRAND JUNCTION, COLORADO

WALKER FIELD - ILS RWY 11

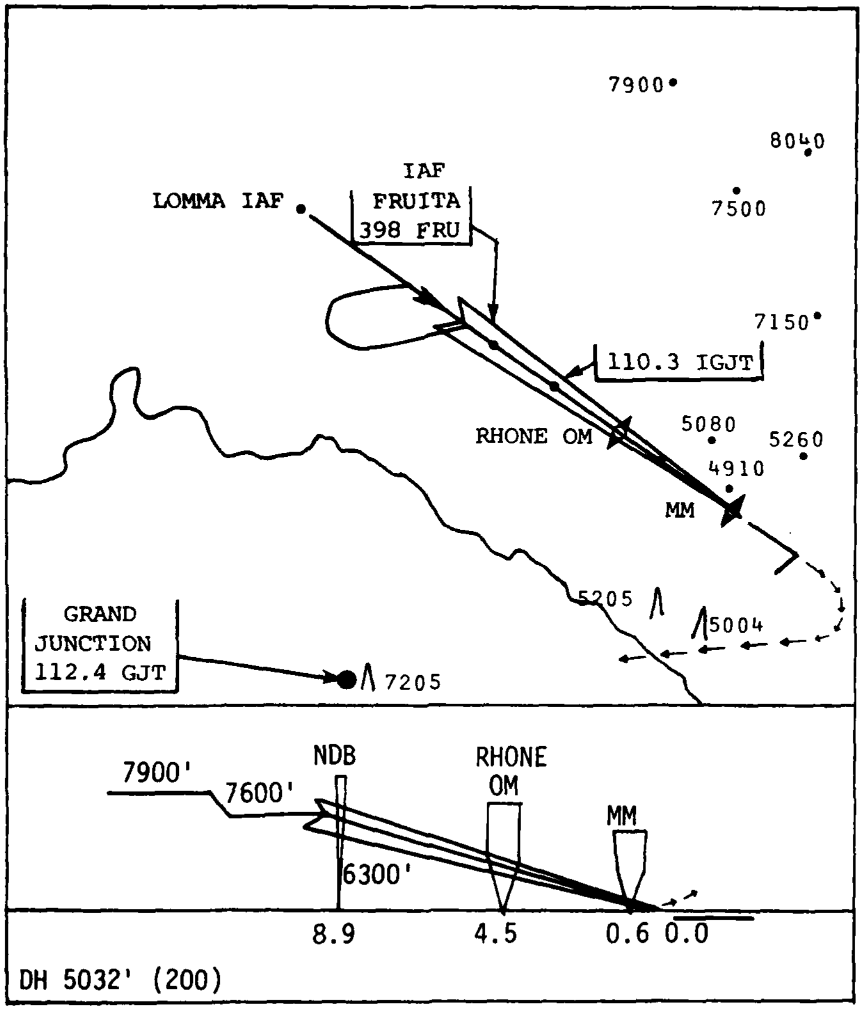


Figure 4.7 Existing ILS Approach At Grand Junction, Colo.

The RNAV/Loran-C test approach duplicated the ground track of the ILS. There were 4 waypoints (Figure 4.8): waypoint 1, the IAF, was 15 nm out and the leg altitude was 7600 feet. Waypoint 2, 10 nm from the runway, was the IF. Minimum altitude between 1 and 2 remained 7600 feet. Descent to 6300 feet was authorized between waypoint 2 and waypoint 3, the FAF. Passing this point, 5 nm out, the minimum descent altitude was 5440 to the MAP, waypoint 4, at the threshold. The missed approach also duplicated that for the ILS.

Twelve (12) approaches were proposed for Grand Junction, 3 were accomplished. A checkout flight for each of the triads was completed and one data flight on the Fallon-Middletown-George triad was flown but, just after the first data flight, the navigator/processor began to have problems. The system did lock-on, once, to the ambiguous solution some 300 nm away, but after it broke lock from that solution, it never again was able to acquire a usable navigation signal.

Two portable beacons were used to augment the Grand Junction VORTAC DME, 14 nm southwest of the field. One was set up outside the airport fire station with the antenna on a pole attached to a chain-link fence. The other portable was installed on the roof of a private dwelling northwest of the field and west of the final approach course. The RAPPS equipment also made use of the Grand Junction VORTAC DME signal.

In Table 4.1, the number of proposed approaches and the number of actual approaches testify to the difficulties peculiar to this location. A graphic representation of the unfavorable geometry which prevented the navigator from successfully tracking the signal can be seen in Figure 4.9.

4.4 SYSTEM CHECKOUT FLIGHTS

4.4.1 Reno, Nevada

Reno International Airport was chosen for some preliminary Loran-C and data acquisition systems checkout. The existing primary approach to runway 16 (Figure 4.10) is the ILS DME. The approach begins 11.1 nm out at 9000 feet (8500 with no procedure turn). After glideslope intercept, decision height is 5011 feet MSL (600 AGL).

Figure 4.11 shows the RNAV/Loran-C approach developed for the system checkout. It duplicated the plan-form of the ILS. The procedure had 6

GRAND JUNCTION, COLORADO

WALKER FIELD - RNAV/LORAN-C RWY 11

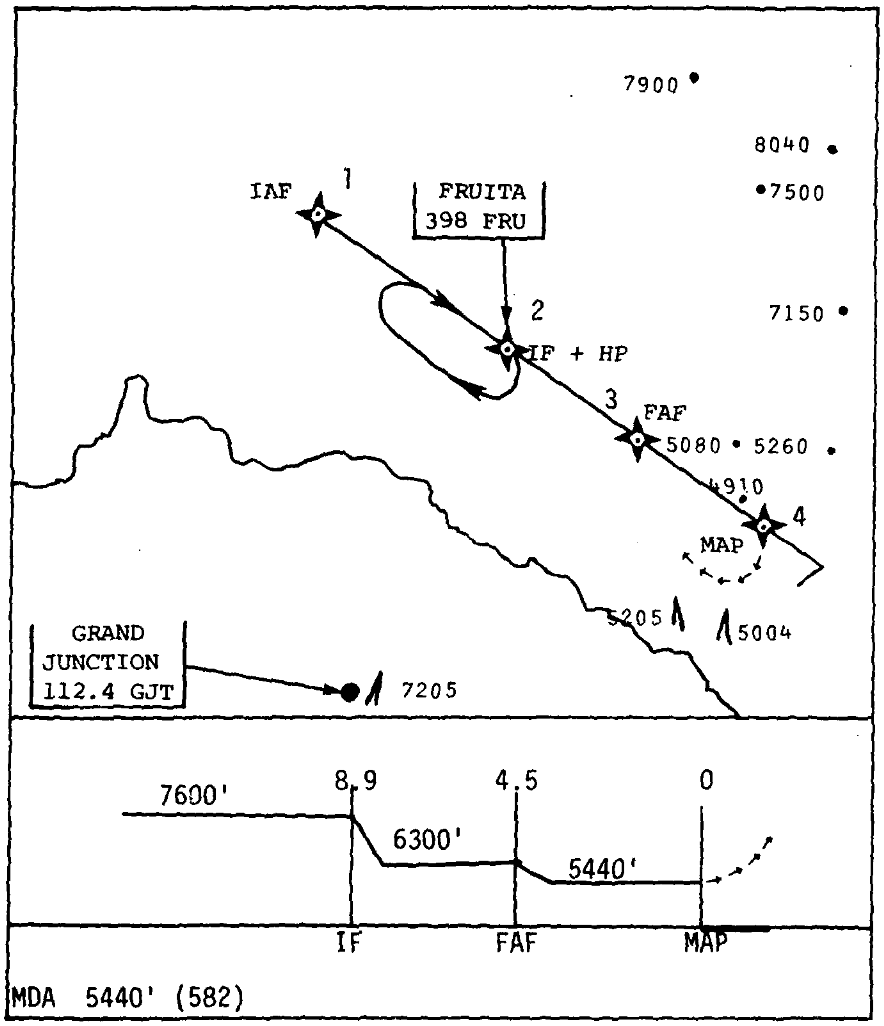


Figure 4.8 Loran-C Test Approach

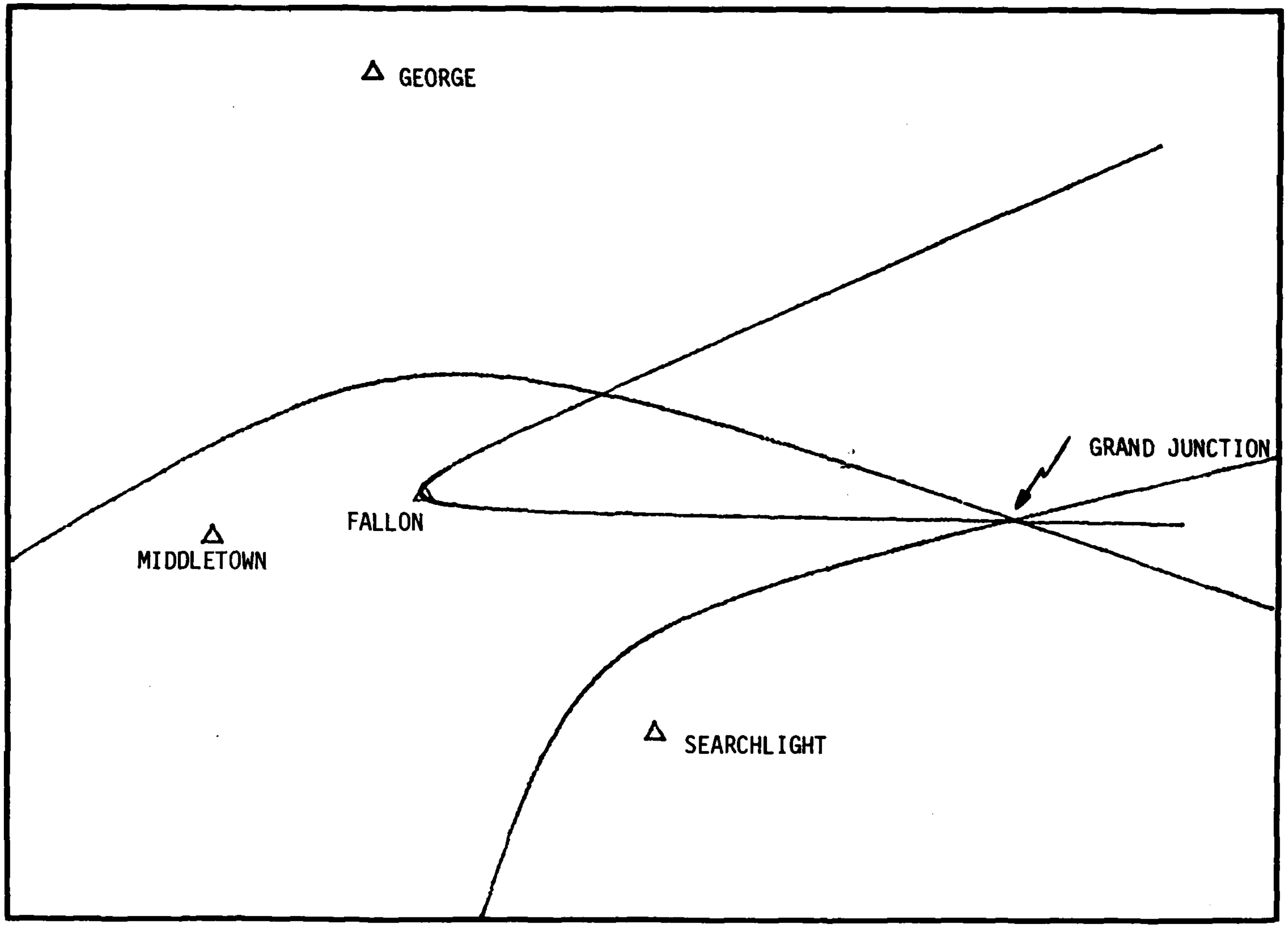


Figure 4.9 West Coast Loran-C Chain Geometry At Grand Junction, Colo.

RENO, NEVADA

RENO INTERNATIONAL - ILS RWY 16

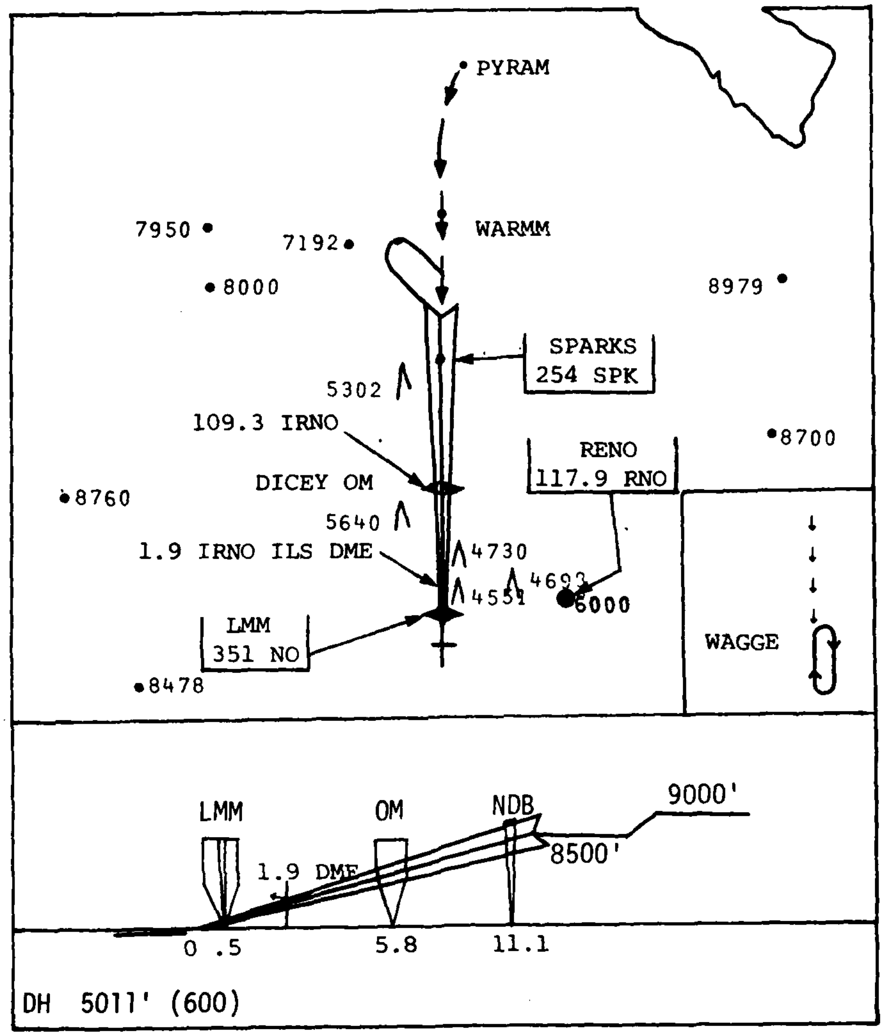


Figure 4.10 Existing ILS Approach At Reno International, Reno, Nevada

RENO, NEVADA

RENO INTERNATIONAL - RNAV/LORAN-C RWY 16

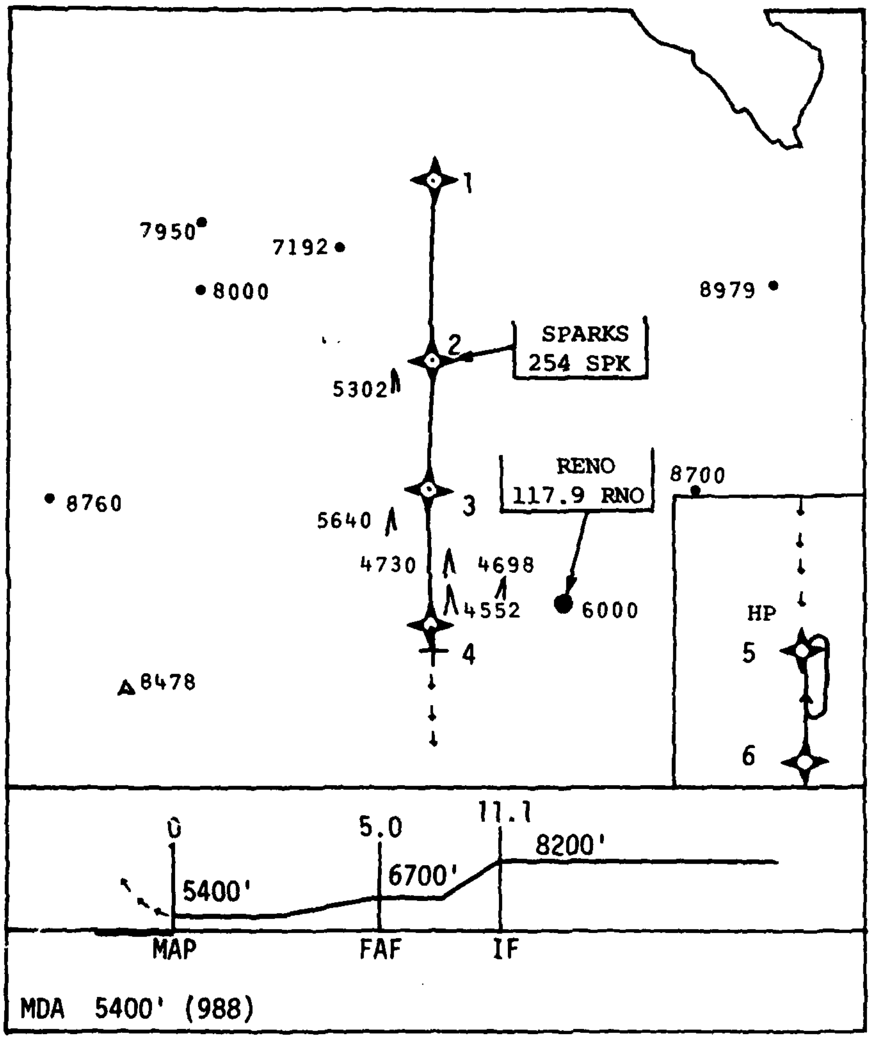


Figure 4.11 Loran-C Test Approach

waypoints. The IAF was 15 nm out at waypoint 1, at no lower than 8200 feet MSL. Five (5) nm later, at the IF (WP 2) 10 nm from the threshold, the minimum altitude was still 8200 feet. From WP 2 to WP 3 (the FAF) 5 nm out, descent was authorized to 6700 feet. Between WPs 3 and 4 (the MAP) the minimum descent altitude was 5400 feet. Waypoints 5 and 6 defined the missed approach holding point and pattern.

During the three system checkout approaches, beacons were placed on Peavine Peak (northwest of the field) and at Stead Airport, Reno. The RAPPS system also used the Reno VORTAC east of the airport, and the ILS DME on the field for its multilateration calculations.

The checkout approaches were visual approaches (not "hooded"). They were flown on 6 July 1979. Of the three approaches, two were completed and one was cut short at ATC request due to traffic. Data was recorded using both the Fallon-Middletown-Searchlight (FMS) and the Fallon-Middletown-George (FMG) triads.

4.4.2 Reno/Stead

On 21 July 1979, after some aircraft electrical system repairs, 2 tracking passes were flown over runway 26 at Reno/Stead Airport. One pass was flown using the FMS triad, and one was flown with the FMG triad.

The purpose of the tracking passes was to corroborate a 1 nm error first observed during the checkout approaches at Reno International, when the Loran navigator showed 1 nm to go with the aircraft over the runway threshold. The passes did indeed show that a north-south bias existed (see Section 4.5, 21 July 1979 entry).

Analysis of the results of these checkout flights and the major data collection flights is contained in Sections 5.0 and 6.0.

4.5 TEST FLIGHT CHRONOLOGY

The matrix in Table 4.1 contains the entire flight phase of the test.

<u>6 July 1979</u>

Three approaches were flown to runway 16, Reno International Airport (1 broken off by ATC, 2 complete) using the Fallon-Middletown-Searchlight triad (FMS) and the Fallon-Middletown-George triad (FMG).

Their purpose was to test operation of the Loran-C and data acquisition systems.

The Loran functioned well, giving steady CDI steering. Lateral positioning with respect to runway centerline was excellent throughout. At the threshold, the Loran-C had positioned the aircraft within 500 feet of centerline, but read 1 mile to go to the threshold waypoint. The 1 mile error was noted in the air as well when the FMG triad was selected.

During the initial phases of all 3 approaches, at about 13 nm from the threshold, the Loran broke lock for about 30 seconds. No definite cause for this behavior could be established but a study of the quad charts for that area revealed a powerful, commercial radio station near the extended runway centerline at about 12 miles from the threshold.

On the 3rd approach (a complete one) the Loran-C system broke lock for about 30 seconds at about 2.5 miles from the threshold. Steering was regained and remained steady for the remainder of the approach.

Since the placement of the TDL-711 CDU was outside the pilot's field of vision, the technique used by the pilot and copilot/observer was for the copilot/observer to operate the TDL-711 CDU and periodically advise the pilot flying the approach of the distance to next waypoint and minimum descent altitudes as the approach proceeded.

Pilot workload was well within acceptable limits. These approaches were flown visually, that is, the pilot flew the approach referring to the Loran-C guidance but he did not wear the instrument hood.

Flight time was 1.5 hours.

<u>7 July 1979</u>

Twelve (12) approaches were planned to runway 18 at Lake Tahoe Airport. Two visual approaches were flown recording data, and 1 partially-hooded approach was flown using Loran but not recording data due to failure of the right alternator, which shut down the data acquisition rack.

The first visual approach was flown on the FMS triad. Loran steering was stable and smooth throughout. At the threshold the Loran had positioned the aircraft .12nm right of the runway, but showed 1 nm to go to the threshold waypoint.

The FMG triad was selected for the second visual approach. Again, steering was steady and consistent with the extended runway centerline. At the missed approach point (MAP) the aircraft was slightly left of the runway and the TDL-711 CDU showed 0.0 nm to go to the threshold waypoint.

During the third approach, power to the data recording equipment was interrupted when the right engine alternator failed. The approach was flown using the Loran-C only. The initial portion was flown "hooded", with the last leg flown visually. The FMS triad was reselected for this approach. Loran steering was steady and true to centerline. At the threshold, the aircraft was about .25 nm left of the centerline, and the CDU showed 0.3 nm to go.

The aircraft was then returned to Stead Airport for repairs. Flight time was 2.0 hours.

<u>21 July 1979</u>

With aircraft repairs completed, and the data acquisition equipment re-installed in the aircraft, 2 test runs were flown to runway 26 at Stead to test the Loran-C tracking. These were not approaches, but constant altitude tracking passes.

Triad FMS was used for 1 pass. The aircraft tracked 0.9 nm south of the runway, and the CDU showed 0.1 nm to go at the threshold.

The pass made with the FMG triad selected resulted in the aircraft tracking 0.3 nm north of the runway, and the CDU displaying 0.1 nm to go at the threshold.

Flight time was 2.2 hours. This total includes an earlier flight during which technical difficulties prevented data recording.

<u>22 July 1979</u>

The aircraft was repositioned to Klamath Falls, Oregon. Flight time was 1.9 hours.

<u>23 July 1979</u>

Prior to flying 2 visual approaches to runway 32 at Kingsley Field, a ramp check of the Loran-C using the FMG triad agreed with the computed ramp position within 0.1 min. The Loran would not lock on the FMS triad (Kingsley Field is on the F-S baseline extension).

The FMG triad was used for the 2 visual approaches. Loran guidance was again steady and on centerline throughout. At the threshold on both approaches, the Loran-C had positioned the aircraft about 300 feet east of centerline, and the CDU showed 0.1 nm to go.

An attempted in-flight lock on the FMS triad was not successful. Flight Time was 0.7 hours.

<u>24 July 1979</u>

As a result of the unsuccessful attempts to lock on the FMS triad, 6 approaches (3 by each pilot) were flown "hooded" to runway 32 at Walker Field using the FMG triad.

Loran-C guidance was again steady and on centerline, with displacement at the threshold about 300 to 400 feet east in each case, and the CDU showing 0.1 nm to go.

During 1 approach, the Loran TDL-711 broke lock twice, for about 30 seconds each time, but re-acquisition occurred smoothly, and further steering was steady.

Flight time for the approaches was 2.6 hours.

The aircraft was then returned to Reno International in preparation for the data flight at Lake Tahoe. Flight time was 1.5 hours.

<u>26 July 1979</u>

Ten (10) approaches were flown to Lake Tahoe Airport.

During the first 3 approaches, using the FMS triad, Loran guidance was generally good, although at about 2.5 nm to threshold the Loran veered slightly left and slowly corrected back to centerline at the threshold. Typically the aircraft was 300 to 500 feet left of centerline and the CDU showed from 0.1 to 0.4 nm to go.

The next 2 approaches were flown using triad FMG. Loran steering was good, but again veered at about 2.5 nm to threshold, this time to the right of centerline. Displacement values at the threshold conformed to those using the FMS triad, and distances to go were similar.

The next 3 approaches were flown using the FMG triad with the TDL-711 area-calibrated on the ramp at Lake Tahoe Airport. The Loran-C guidance was steady and consistent. The same tendency to veer off centerline at about 2.5 nm to threshold was evident, with good con-

vergence back to centerline by the threshold. The aircraft was typically 300-500 feet displaced to the right at the threshold, and distance to go displays improved slightly to 0.0 and 0.1 nm to go.

The last 2 approaches were flown on the FMS triad, non-area-calibrated, and the Loran guidance and behavior was similar to earlier approaches using this triad, and the displacement was again to the left.

Loran guidance was strong down to the runway surface.

The aircraft was returned to Stead for service. Flight time was 4.4 hours. After service, the aircraft was moved to Reno International prior to departure for Grand Junction. Flight time was 0.4 hours.

<u>27 July 1979</u>

The aircraft was moved to Grand Junction, Colorado in preparation for approaches there.

Enroute, using the FMG triad, the initial accuracy was very good with occasional, short-duration breaks in lock.

Closer to Grand Junction to accuracy began to degrade until position error was about 10 nm at landing.

After landing, the FMG/FGS PROM was again installed and ramp checked with the FMG triad, Loran-C position differed from ramp position by a considerable amount: 6.5 min. further north and 18.0 min. further west.

Loran-C position with the FGS triad selected differed from the ramp position by 0.5 min. north and 0.7 min. west.

<u>28 July 1979</u>

An area calibration was attempted with the FMG triad selected, but the TDL-711 would not accept the calibration exactly as entered. N39° 07.5' W108° 32.0' was entered. N39° 07.3' W108° 31.3' was accepted. The reasons for this apparent discrepancy are discussed in Section 6.0.

A visual approach was flown under the area calibration. Loran-C guidance was good but not as steady as during previous test approaches. At the threshold the aircraft was about 800 feet left of centerline, and the CDU showed 0.5 nm to go.

The next approach was "hooded". Steering was similar to the visual approach, however at the threshold the Loran broke lock, and when it

locked again it had settled at N41° 11.2' W114° 55.9', a point about 300 nm west. Subsequent calculations show the point to be the other possible intersection of the LOPs, the alternate solution.

The area calibration was deleted and the FGS triad selected. A visual approach was flown during which the Loran guidance was good. At the threshold the aircraft was about 800 feet right of centerline and the CDU displayed .4 nm to go.

The next approach was begun "hooded". Almost immediately the Loran-C broke lock and it never locked on again. The approach was continued using the localizer and a final ILS approach was flown while continuing to record data on the FSG triad, after which the test was terminated. Aircraft flight time was 1.6 hours.

Of the 64.4 hours flown during the flight test phase, 47.5 hours were required to position the aircraft at the test locations and return it to West Palm Beach, Florida. Equipment checkouts inflight account for 4.1 hours. Data acquisition flights required 12.8 hours.

5.0 DATA REDUCTION PROCESS

Due to the unique nature of the data which resulted during the Loran-C West Coast Chain test program, special procedures were developed for the recovery and analysis process. The following subsections discuss in detail the characteristics of the data acquired, the techniques used to derive ground truth positioning information, the recovery and processing of the Loran-C data, and the error analysis and plotting techniques applied.

5.1 CHARACTERISTICS OF THE DATA

The data acquisition system utilized for these tests was developed under FAA contract to Amex Corp. (with subcontracts to Sierra Nevada Corp.). It was designed to accomplish three objectives:

- Serve as a data collector system
- Provide precision DME ranging to multiple DME beacons
- Serve as housing, power supply, etc. for the navigator under test.

The precision ranging function was designed to provide position information through the use of multilateration techniques, and to therefore serve as a portable instrumented range for evaluating navigation equipment. Hence, the name Remote Area Precision Positioning System, Version 1 (RAPPS-1) was given to the system. A further system capability, real-time display of RAPPS-derived position and navigator-sensed position, was available but not used during these tests.

The RAPPS system acquires and records data from the following sources:

1) DME--Six channels of DME information available at the rate of one channel per second. Each channel contains five characters of DME distance (in units of hundredths of miles) and a one-character channel ID.
2) TDL-424--A 13-character data field containing navigation information (the TDL-424 was not installed during this test)
3) TDL-711--Four 11-character data fields. One or more may be filled with the data being displayed on the TDL-711 CDU. (The number of appearances of the data, and the timing associated with each field, depends on the rate at which the navigator is updating the CDU at any given time.
4) Altimeter--A 3-character field containing baro-uncorrected altitude in hundreds of feet.

5) Date and Time -- A 14-character field containing month, day, hour, minute and second.

6) TDL-711 -- 157 bytes of internal navigator data in binary format (known as the RDU data stream).

The data acquired from the first five sources was assembled into a 110-character record by the data collector subsystem (an Intel System 80 microcomputer) and is recorded on a standard data cartridge medium (3M type DC 300A cartridge) utilizing a Tektronix Model 4923 recorder unit. The data is recorded using standard ASCII coding. The data acquired from the sixth source is in binary, rather than coded, form. A combination of both sets of data (ASCII and binary) was recorded on similar data cartridges using a Tandberg Model SCDR-3000 recorder. This latter tape format was utilized in the data recovery process. The coding scheme used in the 157-byte TDL-711 data record is documented in Table 5.1.

Control of the multi-channel DME ranging system is exercised by a specially-designed interface unit connected to the data collector computer. It controls the timing of DME channel selection. The timing during this test was set to slightly greater than 1.0 seconds per channel, yielding a cycle time of 6 seconds (nominal) per scan. Within the data collector, timing of the data output process is controlled by the data received from the DME interface, such that one record is written at the end of each DME scan, e.g., every six seconds.

When a data record is written, the contents reflect the status of each of the data buffers in their most recently updated state. Therefore, the time read can be as much as one second old. It was found, due to a characteristic of the TDL-711 navigator that, although it was programmed to transmit a new CDU and RDU data stream once per second nominally, there often occurred interruptions to that process. The data collector program was designed under the assumption that data would be transmitted once per second; therefore, time tags were not associated with the individual data items as they were received. Because of this it is not possible to reliably determine the age of the data within the six-second scan interval. For purposes of the analysis, it was assumed that the Loran RDU data represents the state of the navigator one second prior to clock time. The individual DME channels are also not time coded, but

Table 5.1 RDU Data Formatting

FAA OUTPUT - SIGNIFICANCE AND SCALING OF WORDS

Note: Least significant bit (designated b0) is output first in all words.

WORD	QUANTITY
1	Identifier = AA
2	CDU annunciators (North, South, East, West) b0 (LSB) = W b1 =E b2 =S b3 =N b4 =R b5 =L (b0–b5: 1 = OFF, 0 = ON)
3-5	LH display to CDU (wd3 = LEFT MOST DIGITS)
6-8	RH display to CDU (wd6 = LEFT MOST DIGITS)
9	From/To display to CDU
10	Decimal points and lamps to CDU b0= Hold b1= Legchange b2= Offset (b0–b2: 1=ON, 0=OFF) b3= All other decimal points (0=ON) b4= RH display decimal point #5 (0=ON) b5= RH display decimal point #3 (0=ON) b6= LH display decimal point #5 (0=ON) b7= LH display decimal point #3 (0=CN)
11-12	Distance in BCD. 4 digits as displayed on CDU. LSD=tenths of a n mile. (WD11=most significant digits)
13-14	Ground speed in decimal as displayed on CDU. LSD=knots. (WD13 = most significant digits)
15	Unused
16	CDU switch status b2, b1, b0 = octal selector

	switch position: 0=OFST/VAR 1=TKE/TK 2=XTK/DTK 3=ETE/GS 4=DIS/BRG 5=PRES. POSN.. 6=WPT b3=TD/LL (1=TD) b4=Area (1=Area 2) b5=Test (1=Test)
17	ETE Flag (FF= <300 mins) (ETE=Estimated Time Enroute)
18	Waypoints MSD = 'From' waypoint number (F=blank) LSD='To' waypoint number
19-20	No significance (Fast loop indirect address)
21	Hold flag FF=Hold
22	CDI Scale Factor. (Full Scale deflection =1.28/r nautical miles, for r=00 to 07, where r=scale factor)
23-26	Binary Time difference A. Sixteenth bit (LSB of second byte) = 5 μ s. Total of 32 bits or 4 bytes.
27-30	Time difference B. Same format as TDA.
31-38	Base time differences A & B used in slow loop coordinate conversion. Format as for TDA.
39-46	Delta TDA & TDB. Difference between base TD and actual TD. (Scaling same as Wds 23-26)
47-50	Delta Latitude. Two's complement binary difference between actual Latitude and base latitude (Actual = Base + Delta). 32 bits or 4 bytes. 9th bit (MSB of second byte) is scaled as 1 degree.
51-54	Delta Longitude. As above, but for longitude.

55-58	**Base cross track error. Slow loop output used in calculation of cross track error. Same format and scaling as words 67-70.**
59-66	Cross track gradients with respect to latitude and longitude. 32 bits. Scaled as bit 17 (MSBA byte 3) = 60 ft/deg. Used in calculating of cross track error..
67-70	Cross track error. 32 bits. 24th bit (LSB of byte 3) Scaled as 60 ft.
71-74	Base Latitude. 32 bits. Ninth bit (MSB of byte 2) Scaled as 1 degree. Updated only every 10-20 secs. South = negative (2's complement)
75-78	Base Longitude. Format as Latitude. West = negative
79	Track Status. 0=Track, 1=not track (b0=LSB) b4= Master b3= Secondary A b2= Secondary B b1= Secondary C
80	Master SNR. 8 bit binary number, HEX value=0-70
81	Secondary A SNR
82	Secondary B SNR
83	Blink Status 1=Blink, bit positions as for track status.
84	Enveloping Status b6=Master Lost (1=lost) b5=Master in search (1=search) b4=Master in enveloping state (Fine envelope, track or float) b3=Secondary A in envelope state b2=Secondary B in envelope state b1=Secondary C in envelope state
85	Secondary C SNR
86	Unused
87	Track Status as for 79

RDU Data Formatting
(continued)

88	Envelope number for master. Binary number with value from 00 to FF in hex.
89	Envelope number for secondary A
90	Envelope number for secondary B
91	Blink status as 83
92	Enveloping status as 84
93	Envelope number for secondary C
94	Unused
95-99	"From" Waypoint Latitude in radians. This is in a 5 byte floating point format, having an 8 bit signed exponent with complemented sign bit, followed by a 32 bit signed 2'S complement mantissa with an assumed binary point between the 2nd and 3rd most significant bits (MSB=sign bit) and hence a normalized value between 1 & 2 (e.g. unity is represented by 80 40 00 00 00 in hex) as before South is negative.
100-104	"From" Waypoint Longitude in same 5 byte floating point format as Latitude. West is negative.
105-109	"To" Waypoint Latitude in floating point radians.
110-114	Sine of "To" Latitude in floating point format.
115-119	Cosine of "To" Latitude in floating point format.
120-124	"To" Waypoint Longitude (in floating point radians)
125-129	Bearing of leg between "To" and "From" Waypoints. (in floating point radians)
130-133	Waypoint 0 Latitude. 4 bytes, first byte = FF for South, 00 for North, bytes 2, 3 & 4 in BCD format with a blank represented by hex F.

RDU Data Formatting
(continued)

134-137	Waypoint 0 Longitude - Format as above with FF in first byte for West Longitude.
138-141	Waypoint 0 time difference A - 4 bytes, first is unused (normally FF), bytes 2-4 in BCD format.
142-145	Waypoint 0 time difference B in same format.
146-149	Offset in same BCD format as 130-133. Left is negative (FF)
150-153	Mag Var in same format. West is negative (FF).
154	Display blanking flag. Used to indicate banking of invalid displays when no valid leg is inserted..
155	Triad in Use (00=A, B, C. 01=M, B, C. 02= M, A, C. 03=M, A, B)
156	Track flag. FF=Triad in track.
157	Number of GRI's per CDI update. (See P13 of IDS programming manual.)

are recorded in a specified order with respect to time. In that ordering the last channel measured is recorded first, with the remaining five channels being recorded in reverse order.

In order to recover and reduce the data, the recording unit (Tandberg Model SCDR-3000) was removed from the RAPPS instrumentation rack and connected via its self-contained standard serial interface to the microcomputer system resident at the SCI (Vt.) facility at West Palm Beach. The facility, illustrated in block diagram format in Figure 5.1, includes all requisite functional capabilities for data recovery, processing, error analysis and plotting.

5.2 GROUND TRUTH DATA PROCESSING

In this section the precision ranging system and the techniques utilized to derive an accurate estimate of actual aircraft position from those range measurements are discussed in detail. The method utilized to make range measurements was based on a slightly modified King KDM-7000 DME interrogator. This unit is compatible with standard ICAO DMEs, including all TACAN installations, plus several DMEs acquired specifically for these tests (Butler Model 1020 DME Ground Stations). In addition, highly portable Vega Model 316-L transponder beacons, which also operate at L-band, worked well with the KDM-7000 interrogator even though they are not designed to be fully compatible as an ICAO DME ground station. Both types of supplemental beacons, as well as existing permanent TACAN and DME installations, were used during the conduct of the West Coast Chain flight test program.

The data which resulted from the test program exhibited characteristics which might well be expected from an ICAO DME-based multilateration system, particularly considering the ranging techniques utilized in the RAPPS-1 system. In that system each DME measurement (one channel per second) is made utilizing the KDM-7000 fast acquisition capability. This capability enables the DME to acquire a range value in a nominal acquisition time of ¼ second. This technique works reasonably well. In many cases, depending on range, terrain masking or multipath conditions, it may take longer to acquire, or will not acquire at all within the one-second time slot allowed.

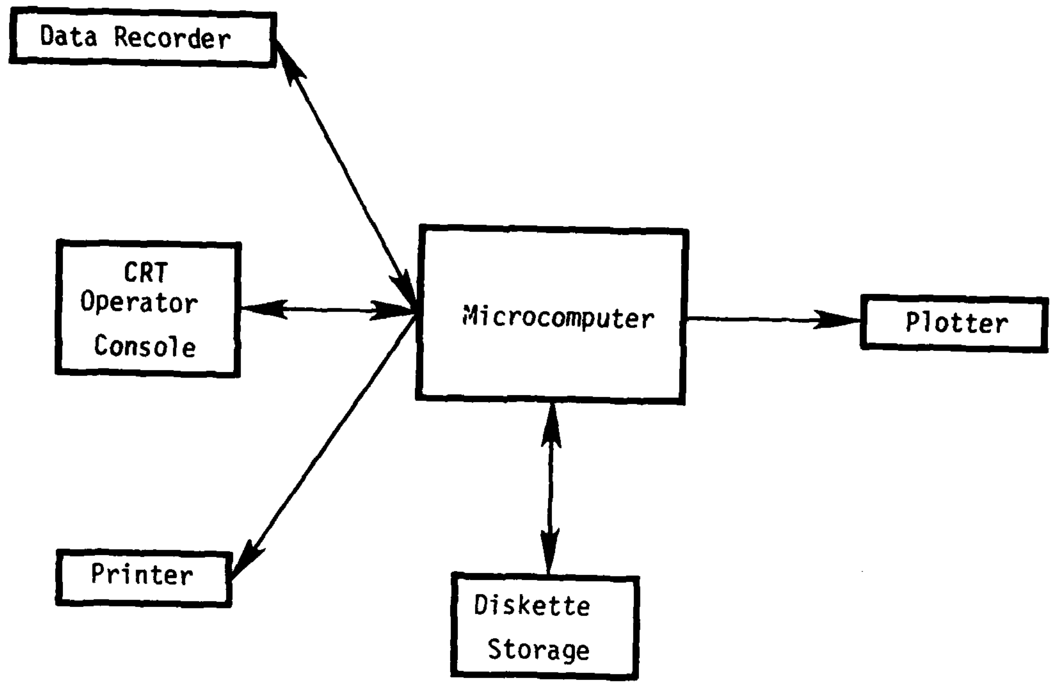


Figure 5.1 Data Reduction System

No redundant information sources are utilized to enhance the capability of the KDM-7000 to acquire the beacons or to pass judgment on the measurements which result (candidate redundant information sources could include immediate DME measurement past history, or aircraft airspeed/heading data). As a result, the DME can give false readings without any indication given that they are in error. The occurrence rate of seemingly false indications was highly correlated with factors that influence signal strength and multipath propagation. For example, as the aircraft descended on approach and a beacon was lost due to terrain, false indications would sometimes result, probably the result of multipath. A condition particularly conducive to multipath was encountered during the approaches to South Lake Tahoe airport. Primary beacon coverage was obtained from Lake Tahoe VOR and a beacon established at Meeks Bay, plus a beacon established on the airport near the tower (See the Lake Tahoe beacon layout in Figure 3.6). A review of the data shows that in much of the data from the airport beacon, the DME was unable to acquire. Furthermore, in many of the cases where it did acquire, the readings were erroneous (inconsistent with the data derived from the other beacons, or inconsistent within itself as compared to other nearby readings). This occurred even though there is no obstruction between the beacon and the aircraft. It is hypothesized that the cause of this behavior lies in the proximity of the beacon to the lake itself, allowing the lake to serve as a radio reflector causing signal canceling. When the primary signal was effectively canceled, the DME would then sometimes acquire some other signal reflected from a building or the nearby hills. As a result of these problems, extra steps were taken in order to discriminate against the erroneous data when it occurred. These techniques are discussed later in this section.

With the exception of the multipath problem, the DME system worked well and provided reasonably accurate data. There are two methods available to demonstrate the accuracy of the system. Since there was no precision independent tracking information available during these tests, a definitive analysis of RAPPS precision is not possible here. The first demonstration of RAPPS precision is to review range measurements which were taken at ground static test points. The second method is to examine the residual errors in the measurements which result when

three or more beacons are being tracked at any one time. The residual errors are defined as the differences between the actual DME range measurements made and the computed distance to each corresponding beacon from the estimated aircraft position. If only two stations are being received, the residuals are always zero since there is a singular solution to the two intersecting DME arcs. When three or more DME measurements are available, the three or more arcs will not intersect at a single point, but will form a triangle due to the fact that some ranging errors will be present. The multilateration technique used to solve for position (discussed later) minimizes the square of the ranging errors. The residual errors thus can not represent the error present in each individual measurement, but, taken together, do represent the consistency of the measurements. Since the locations of the beacons are well known and biases, if present, can be estimated, the residual errors demonstrate the overall accuracy of the measurements at any given time. To illustrate, assume that two range measurements are perfect and the third is wrong by .05 nm, the error would be distributed among the three residuals, with probably no more than .03 nm resulting in any single channel. While there is no indication as to which channel is in error, it may be assumed that the error is no greater than twice the largest residual value.

Ground static calibration tests were taken at two locations, Stead Airport, Nev. and Klamath Falls Airport, Oregon. The results of these tests are listed in Table 5.2, and they illustrate some of the problems discussed to this point. Reviewing the Stead data, it can be seen that three of the four beacons exhibit very small errors, on the order of .02 nm (120 ft.). Four measurements were made on the fourth beacon (Reno VOR), three of which showed an error of .10 nm, while the fourth measurement yielded zero error. It is instructive to note that the first three beacons were within line-of-sight of the aircraft, while Reno VOR was behind a large hill. Thus it is probable that the erroneous measurements represent lock-on to multipath signals.

At Klamath Falls, Oregon, a similar situation prevailed. Two of the beacons, Klamath VOR and the Stuckel Mountain installation were within line-of-sight, while the third, Spring Lake, was located behind intervening terrain. The data from the first two is very stable, while the measurements

Table 5.2 Ground Static Calibration Data

AIRPORT	BEACON SITE	ACTUAL RANGE	RANGE MEASUREMENTS	MEASUREMENT ERRORS
Stead, Nev.	Stead Airport	0.3112	0.32, 0.32	.01, .01
	Peavine Mt.	5.2700	5.29, 5.29	.02, .02
	Desert Research Inst.	1.0434	1.03, 1.03	-.01,-.01
	Reno VOR	12.4388	12.53, 12.44	.09, .00
	Reno VOR	12.4388	12.54, 12.54	.10, .10
Klamath Falls, Oregon	Stukel Mt.	6.1879	6.24, 6.24, 6.25, 6.24	.05, .05, .06, .05
	Stukel Mt.	6.1879	6.24, 6.24, 6.25, 6.25	.05, .05, .06, .06
	Stukel Mt.	6.1879	6.25, 6.25, 6.24, 6.24	.06, .06, .05, .05
	Spring Lake	3.9192	4.25, 4.08, 4.09, 4.14	.33, .16, .17, .22
	Spring Lake	3.9192	4.10, 3.88, 4.13, 4.12	.18, -.04, .21, .20
	Klamath VOR	1.0207	1.09, 1.09, 1.09, 1.09	.07, .07, .07, .07

from the third are quite variable. It is of interest to note that, in the actual data reduction process, beacon biases were estimated and selected in order to minimize the residual errors in the position estimate. The biases which resulted (Stuckel Mt.: 100 ft., Spring Lake: 0 ft., Klamath VOR: 500 ft.) do not correspond exactly to the measurement errors in Table 5.2. This is not really unexpected since the performance of DME in general when airborne is typically better than when on the ground, due to the effects of terrain and nearby buildings at an airport.

The data reduction technique utilized to extract aircraft position (ground truth) information from the available DME data was carefully designed to minimize the effects of random DME error sources, to eliminate the time skew present within the data, and to minimize the effects of temporary data dropouts on data availability from any given beacon. Time skew results from the sequential nature of the measurement (one per second) process. The basic technique applied was to include all DME measurement information available within ±12 seconds of each point in time of interest. The times of interest are those specific times for which Loran-C data is available (once every six seconds). The resulting 24-second time period will contain up to five measurements from each channel. The procedure used is a four-stage process which utilizes a buffer six DME channels wide, and in excess of twenty-four cells (seconds) long to hold all of the DME information:

Stage 1: Data from a channel referencing the same beacon as a lower-numbered channel is added to the data in that lower numbered channel.

Stage 2: A least-square linear curve fit is applied to each channel containing data to result in a linear equation of DME distance versus time which is valid over that time interval. Several logic tests are applied to the data in each channel to see if sufficient points are available to provide a valid estimate, and to avoid extrapolating from data far removed from the time of interest.

Stage 3: The linear equations for each channel are solved substituting the time of interest to yield estimated DME range values for each channel at the time of interest. These range values are corrected for slant range error (aircraft and beacon altitudes are known).

Stage 4: A least-square, iterative multilateration solution technique is applied in X-Y coordinates. The resulting X-Y aircraft position is then supplied to the error analysis portion of the program (see Section 5.4).

The linear least-square fit technique applied to the DME data utilizes standard equations:

where r_1, r_2... are range measurements made at times

t_1, t_2..., a linear relationship

$$R = b_0 + b_1 T \qquad \text{I}$$

can be defined given n such measurements, as follows:

$$b_1 = \frac{n\Sigma r_i\, t_i - \Sigma r_i \Sigma t_i}{n\Sigma t_i^2 - (\Sigma t_i)^2} \qquad \text{IIa}$$

$$b_0 = \frac{\Sigma r_i}{n} - b_1 \frac{\Sigma t_i}{n} \qquad \text{IIb}$$

A set of coefficients (b_0, b_1) is calculated for each of the channels containing DME measurements.

The iterative, linear least-square technique to perform multilateration in an X, Y coordinate system can be derived as follows:

Given that there are N beacons located at coordinates X_i, Y_i, and that the least-square solution for aircraft position is at coordinates X, Y, then given that an estimate for aircraft position is available which is $\hat{X}$, $\hat{Y}$:

δ, ε are defined as the error in the estimate:

$$X = \hat{X} + \delta$$
$$Y = \hat{Y} + \varepsilon \qquad \text{III}$$

The problem is to compute estimates of δ and ε given $\hat{X}$ and $\hat{Y}$, update the values for $\hat{X}$ and $\hat{Y}$, and iterate until δ and ε are small.

The range from the least-square solution to each beacon is:

$$r_i{}^2 = (X - X_i)^2 + (Y - Y_i)^2 \qquad \text{IV}$$

Substituting equations III into IV, expanding and collecting terms yields:

$$r_i^2 = \hat{r}_i^2 + 2\,\delta(\hat{X} - X_i) + 2\,\varepsilon\,(\hat{Y} - Y_i) + \delta^2 + \varepsilon^2 \qquad \text{V}$$

Assuming δ and ε are small, the squared terms may be neglected. Rearranging terms and using an approximate technique for computing square root yields:

$$r_i - \hat{r}_i = p_i\,\delta + q_i\,\varepsilon = \Delta r_i$$

$$\text{where } p_i = \frac{\hat{X} - X_i}{\hat{r}_i} \qquad \text{VI}$$

$$q_i = \frac{\hat{Y} - Y_i}{\hat{r}_i}$$

This yields a simultaneous independent pair of equations whose solution is the estimate of least-square fit:

$$\Sigma\Delta r_i = \Sigma p_i\,\delta + \Sigma q_i\,\varepsilon$$

$$\Sigma p_i \Delta r_i = \Sigma p_i^2\,\delta + \Sigma p_i q_i \varepsilon \qquad \text{VII}$$

summed over N beacons

The solutions for δ and ε may be found by the method of determinates. They are added to $\hat{X}$, $\hat{Y}$ to yield new estimates and the process is repeated until δ and ε become small. In the implementation of these equations for data reduction, usually three or four iterations were required.

The resulting system performs well when operating on reasonably accurate ranging data, and is efficient regarding computer time requirements. However, the least-square fit technique possesses no ability to recognize and reject erroneous range measurements, such as those which result from multipath effects. Since some of the data was found to be contaminated to a certain extent with multipath, a further step was taken to test the DME readings for potential errors. It was not possible to utilize the estimate which results from the multilateration technique to judge the data, since its output is twelve seconds behind the incoming data steam of DME measurements. To overcome this problem a tracking filter technique was implemented. This technique was based

on commonly-used α, β tracker techniques, as discussed in detail in Reference 1. The technique selected was designed based on reasonable assumptions concerning aircraft dynamics and expected (normal) DME error variance. The filter was configured to be oriented in the direction of motion of the aircraft, such that different values for expected accelerations in the longitudinal and transverse coordinate directions could be used.

The tracking filter can be expressed as a two stage process: smoothing of sensor data, and prediction. The smoothing equations are:

$$\hat{X}(n) = \hat{\hat{X}}(n) + \alpha(n)[Z(n) - \hat{\hat{X}}(n)]$$
$$\hat{\dot{X}}(n) = \hat{\hat{\dot{X}}}(n) + \beta(n)[Z(n) - \hat{\hat{X}}(n)] \qquad \text{VIII}$$

Where: $\hat{X}(n)$ and $\hat{\dot{X}}(n)$ represent system state (x and y coordinates) up to and including the measurement taken at time n; $\hat{\hat{X}}(n)$ and $\hat{\hat{\dot{X}}}(n)$ represent system state up to but not including the measurement taken at time n; Z(n) is the measurement (x and y coordinates) at time n, and $\alpha(n)$ and $\beta(n)$ are the gains. The gains α and β may be time-varying if the error covariances are updated by the filter, or may be constant values based on an estimated DME error value (as was done here).

The prediction equations are:

$$\hat{\hat{X}}(n + 1) = \hat{X}(n) + \Delta t \, \hat{\dot{X}}(n)$$
$$\hat{\hat{\dot{X}}}(n + 1) = \hat{\dot{X}}(n) \qquad \text{IX}$$

These simply propagate the state variables based on their derivatives.

The filter gains are:

$$\alpha(n) = \frac{\sigma_{xx}(n)}{\sigma_{xx}(n) + c^2}$$
$$\beta(n) = \frac{\sigma_{x\dot{x}}(n)}{\sigma_{xx}(n) + c^2} \qquad \text{X}$$

where: c^2 = DME error variance

σ_{xx}, $\sigma_{x\dot{x}}$ and $\sigma_{\dot{x}\dot{x}}$ are the error covariances

The error covariances are found in Reference 1 to be derivable from the following recursive equations:

$$\sigma_{xx}(n+1) = \frac{1}{4} a^2(\Delta t)^4 + \sigma_{xx}(n) + 2\Delta t\sigma_{x\dot{x}}(n) + (\Delta t)^2\sigma_{\dot{x}\dot{x}}(n) - h(n)\,\frac{(\sigma_{xx}(n) + \Delta t\sigma_{x\dot{x}}(n))^2}{\sigma_{xx}(n) + c^2}$$

$$\sigma_{x\dot{x}}(n+1) = \frac{1}{2} a^2(\Delta t)^3 + \sigma_{x\dot{x}}(n) + \Delta t\sigma_{\dot{x}\dot{x}}(n) - h(n)\,\frac{\sigma_{x\dot{x}}(n)\,(\sigma_{xx}(n) + \Delta t\sigma_{x\dot{x}}(n))}{\sigma_{xx}(n) + c^2} \qquad \text{XI}$$

$$\sigma_{\dot{x}\dot{x}}(n+1) = a^2(\Delta t)^2 + \sigma_{\dot{x}\dot{x}}(n) - h(n)\,\frac{(\sigma_{x\dot{x}}(n))^2}{\sigma_{xx}(n) + c^2}$$

where $h(n)$ is set to 1 if data is received at time n, and zero otherwise, and where a^2 is the acceleration variance.
In the data reduction system, these equations (XI) were solved iteratively off line using appropriate values for a, c and Δt in order to derive fixed α and β gain values which will yield optimal filter performance (minimize squared filter error).

The filter can be decomposed into longitudinal (L) and transverse (T) components by expressing the measurement data difference vector

$$D = Z(n) - \hat{\hat{X}}(n) \qquad \text{XII}$$

which appears in equation (VIII) as:

$$D_L = D_X \cos\phi + D_Y \sin\phi$$

$$D_T = D_X \sin\phi - D_Y \cos\phi \qquad \text{XIII}$$

where ϕ is the aircraft heading, or

$$D_L = \frac{D_X \hat{\hat{\dot{X}}} + D_Y \hat{\hat{\dot{Y}}}}{s}$$

$$D_T = \frac{D_X \hat{\hat{\dot{Y}}} - D_Y \hat{\hat{\dot{X}}}}{s} \qquad \text{XIV}$$

where $s^2 = \hat{\hat{\dot{X}}}^2 + \hat{\hat{\dot{Y}}}^2$

we then can express the smoothing equations as follows:

$$\hat{X} = \hat{\hat{X}} + \alpha_L \frac{u \hat{\hat{\dot{X}}}}{s^2} + \alpha_T \frac{v \hat{\hat{\dot{Y}}}}{s^2}$$

$$\hat{Y} = \hat{\hat{Y}} + \alpha_L \frac{u \hat{\hat{\dot{Y}}}}{s^2} - \alpha_T \frac{v \hat{\hat{\dot{X}}}}{s^2}$$

$$\hat{\dot{X}} = \hat{\hat{\dot{X}}} + \beta_L \frac{u \hat{\hat{\dot{X}}}}{s^2} + \beta_T \frac{v \hat{\hat{\dot{Y}}}}{s^2}$$

$$\hat{\dot{Y}} = \hat{\hat{\dot{Y}}} + \beta_L \frac{u \hat{\dot{Y}}}{s^2} - \beta_T \frac{v \hat{\hat{\dot{X}}}}{s^2}$$

Where $u = D_X \hat{\hat{\dot{X}}} + D_Y \hat{\hat{\dot{Y}}}$

$$v = D_X \hat{\hat{\dot{Y}}} - D_Y \hat{\hat{\dot{X}}}$$

which were the equations used in the tracking filter.

The values for α_L, α_T, β_L, β_T were based on the following estimates of DME error and accelerations:

- Standard Deviation of DME Error = 0.02 nm.
- Standard Deviation of Transverse Acceleration = .002 nm/sec^2 (derived from standard rate turn).

- Standard Deviation of Longitudinal Acceleration = .0005 nm sec^2 (derived from assumed acceleration of 2 Kt/sec).
- Update Interval = 1 sec.

The gains which resulted were:

α_L = .20

α_T = .36

β_L = .02

β_T = .08

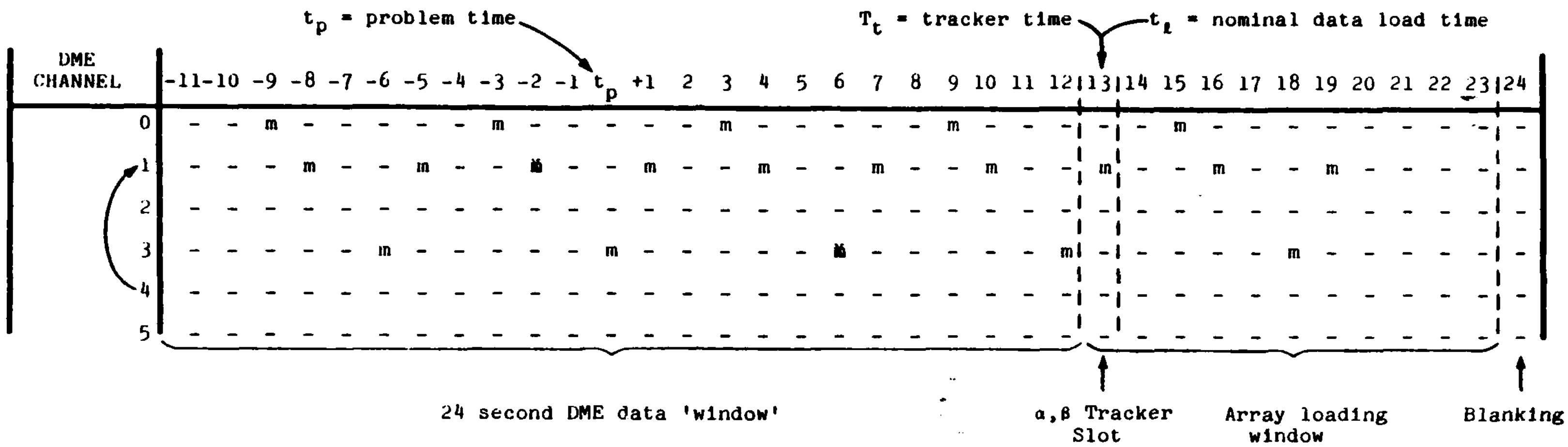
Various other combinations of gains were tested, but these functioned best from the standpoint of data tracking accuracy (lower gains overly smoothed the data) and ability to avoid getting "lost" in the presence of erroneous data (higher gains resulted in too large a response to an erroneous measurement).

The filter functions by examining the DME measurement available each second (when such a measurement exists) and compares it to the range computed from its estimated position and the beacon location. If the difference between them is greater than 0.4 nm it totally ignores the measurement. If the difference is less than 0.4 nm but greater than 0.15 nm, the filter is updated using that measured range, but the data is excluded from the multilateration process. Therefore, data found to be in error greater than 0.15 nm are excluded from the error analysis process.

The entire DME measurement process is illustrated graphically in Figure 5.2. This shows the state of the circular DME data buffer for a case where channel 4 is tuned to the same beacon as channel 1, and where no measurements exist for channel 5.

5.3 LORAN-C DATA PROCESSING

Prior to the conduct of the Loran-C error analysis, the Loran RDU data was converted and displayed in an operationally meaningful format, and used to correlate the data recovered with the manual data log kept for every approach flown. The RDU data was shown to match the logs exactly, and so validated the logs themselves. The data read, converted to meaningful engineering units and printed out by the RDU display program included the following items:



"m" indicates that a measurement exists. "~~m~~" indicates a rejected measurement.

DME ranges calculated at time 't_p' from least square fit.

No range is computed if data is insufficient within a channel.

Multilateration is performed at time 't_p' using the DME channels available.

Figure 5.2 RAPPS DME Data Processing Technique

- Replica of the CDU display
- Indicators of CDU switch positions
- Indications of CDU status light indicators
- Loran distance to waypoint and groundspeed
- Loran time differences
- Latitude, longitude and cross track deviation
- Signal-to-noise ratio data and stations in track
- Station blink status
- Station envelope track status and envelope numbers
- Parallel offset and magnetic variation
- Triad in track

An example of the RDU display output is shown in Figure 5.3.

Another method of displaying the Loran RDU data is through use of a plotting program developed for that purpose. This program plots six parameters versus time:

- Time Differences A and B
- Latitude and Longitude
- Cross Track Deviation
- Along Track Distance

Most of the values are shown as deviations from their initial values at an appropriate scale factor, so that small variations in the data can be visually perceived. Examples of these plots may be found in Section 6.0.

An additional Loran-C data processing task was conducted where the time difference data was converted to latitude and longitude, and compared with the TDL-711 calculation of lat/lon. In addition, the coordinate conversion from latitude/longitude to track-related data (cross track deviation, along track distance) was also duplicated for comparison with TDL-711 derived values.

5.4 ERROR ANALYSIS AND PLOTS

The error analysis program developed for this task combines the results of RAPPS DME data processing, as described in Section 5.2, and the Loran-C RDU data units conversion described in the previous section.

```
07 06 13 20 45                              ---- TDL711 RDU DATA ----                                L070679
                         WPROLH       MTAT                                           SNR          ENV #               I
I--LH DISP--I--RH DISP-IFTLFCDDISTSPEDSLRSI--TDA--I--TDB--I----LAT---I---LONG---I CTD TRK M A B C BLK ENV M A B C   OFF    VAR  IRIF
------------------------------------------------------------------------------------------------------------------------------------
          1.9 0 3 0        1     00190170DL2 28663.79 43892.10  39.47.54.-119.48.10.-1.64MABC55515554   MABC63636265L      E 17   MBCY
          1.8 0 3 0        1     00180170DL2 28663.81 43892.20  39.47.56.-119.48.10.-1.64MABC55505554   MABC63636265L      E 17   MBCY
          1.8 0 3 0        1     00180170DL2 28663.81 43892.20  39.47.56.-119.48.10.-1.64MABC55505554   MABC63636265L      E 17   MBCY
          1.8 0 3 0        1     00180170DL2 28663.81 43892.20  39.47.56.-119.48.10.-1.64MABC55505554   MABC63636265L      E 17   MBCY
          1.8 0 3 0        1     00180170DL2 28663.81 43892.20  39.47.56.-119.48.10.-1.64MABC55505554   MABC63636265L      E 17   MBCY
          1.8 0 3 0        1     00180170DL2 28663.81 43892.20  39.47.56.-119.48.10.-1.64MABC55505554   MABC63636265L      E 17   MBCY
          1.8 0 3 0        1     00180170DL2 28663.81 43892.20  39.47.56.-119.48.10.-1.64MABC55505554   MABC63636265L      E 17   MBCY
          1.9 0 9 7        1   L 00190174DL2 28665.63 43896.85  39.49.47.-119.48. 5.-1.70MABC56545654   MABC62646364L      E 17   MBCY
          1.9 0 9 7        1   L 00190174DL2 28666.06 43897.30  39.49.57.-119.48. 3.-1.67MABC56535655   MABC63646464L      E 17   MBCY
          2.0 1 0 7        1     00200173DL2 28668.01 43898.35  39.50.17.-119.47.51.-1.50MABC56505654   MABC63636364L      E 17   MBCY
          2.0 1 0 7        1     00200172DL2 28669.36 43898.82  39.50.24.-119.47.43.-1.37MABC56505654   MABC63636364L      E 17   MBCY
          2.0 1 1 9        1   L 00200165DL2 28672.99 43899.64  39.50.33.-119.47.18.-1.03MABC55515553   MABC62626365L      E 17   MBCY
          1.9 1 1 9        1     00190159DL2 28675.15 43900.00  39.50.35.-119.47. 3. -.79MABC55505655   MABC62636264L      E 17   MBCY
          1.7 1 3 2        1     00170146DL2 28678.78 43900.33  39.50.31.-119.46.38. -.50MABC55525654   MABC63636264L      E 17   MBCY
          1.6 1 4 3        1   L 00160135DL2 28681.71 43900.45  39.50.24.-119.46.17. -.30MABC56515655   MABC64636465L      E 17   MBCY
          1.3 1 4 3        1   L 00130120DL2 28683.94 43900.40  39.50.14.-119.46. 1. -.02MABC55515655   MABC62636365L      E 17   MBCY
          1.2 1 5 4        1   L 00120111DL2 28686.10 43900.32  39.50. 4.-119.45.46.  .11MABC56525655   MABC63646366L      E 17   MBCY
          1.0 1 5 4        1   L 00100102DL2 28687.46 43900.23  39.49.57.-119.45.36.  .28MABC56515555   MABC64646366L      E 17   MBCY
          0.8 1 6 7        1     00080089DL2 28689.36 43899.75  39.49.37.-119.45.22.  .43MABC56525655   MABC63646367L      E 17   MBCY
          0.8 1 6 7        1     00080089DL2 28689.36 43899.75  39.49.37.-119.45.22.  .43MABC56525655   MABC63646367L      E 17   MBCY
          0.8 1 6 7        1     00080089DL2 28689.36 43899.75  39.49.37.-119.45.22.  .43MABC56525655   MABC63646367L      E 17   MBCY
          0.2 2 0 2        1     00020064DL2 28688.32 43897.90  39.48.52.-119.45.27.  .29MABC56505555   MABC63636466L      E 17   MBCY
          0.1 2 0 2       12   L 00010043DL2 28687.03 43896.72  39.48.26.-119.45.34.  .19MABC55515653   MABC64636367L      E 17   MBCY
          0.2 2 0 2       12   L 00020035DL2 28686.58 43896.25  39.48.15.-119.45.37.  .16MABC56535655   MABC64636467L      E 17   MBCY
           .              12     00050023DL2 28685.95 43895.43  39.47.56.-119.45.40.  .13MABC56495655   MABC64646466L      E 17   MBCY
          6.2 1 6 5       12     00620046DL2 28685.49 43894.64  39.47.39.-119.45.42. -.09MABC56525553   MABC63636466L      E 17   MBCY
          6.6 1 6 4       12     00660090DL2 28685.11 43893.87  39.47.23.-119.45.43. -.13MQBC56515654   MABC63646465L      E 17   MBCY
          6.5 1 6 4       12     00650093DL2 28684.82 43893.42  39.47.12.-119.45.45. -.11MABC55525654   MABC63636464L      E 17   MBCY
          4.9 1 6 4       12     00490102DL2 28684.00 43892.31  39.46.51.-119.45.48. -.06MABC56525654   MABC63646464L      E 17   MBCY
    . . . .4.6 1.6.4. . . 12     00460107DL2 28683.45 43891.56  39.46.35.-119.45.51. -.02MABC55535654   MABC64636463L      E 17   MBCY
    . . . . .   . . . . . 12     35860199DL2 28682.80 43890.57  68. 0.46.-113.44.11.-9.00MABC56515554   MABC63636463L      E 17   MBCY
    . . . . .   . . . . . 12     35840261DL2 28682.37 43889.74  67.59.39.-113.44.36.-9.00MABC56525654   MABC63646364L      E 17   MBCY
    . . . . .   . . . . . 12     38572292DL2 28681.97 43889.02 -71. 4.13.-171.14.15.99.00MABC56545654   MABC63636364L      E 17   MBCY
    . . . . .   . . . . . 12     38874233DL2 28681.52 43888.19 -71.21.46.-171. 7. 3.99.00MABC56505555   MABC62646364L      E 17   MBCY
    . . . . .   . . . . . 12     39185299DL2 28681.09 43887.34 -71.39.24.-170.59.48.99.00MABC55525655   MABC62636264L      E 17   MBCY
    . . . . .   . . . . . 12     39405817DL2 28680.78 43886.72 -71.52. 1.-170.54.32.99.00MABC55525654   MABC62636365L      E 17   MBCY
S .6.9.5.1.2W1.7.0.4.6.912     39676350FL2 28680.51 43885.74 -70. 8.42.-170.46.60.99.00MABC55505655   MABC63646464L      E 17   MBCY
N .1.8.2.0.0W . .0.0.0.012     76084349FL2 28680.42 43885.03 218.20. 3.    0. 0. 0.-9.00MABC56505655   MABC63646465L      E 17   MBCY
N .1.7.5.8.1W . .0.0.0.012     77615932FL2 28680.30 43884.23 217.58. 6.    0. 0. 0.-9.00MABC55525554   MABC63646465L      E 17   MBCY
N .3.9.0.9.7W1.1.9.4.6.512     10783871FL2 28680.18 43883.65  39. 9.42.-119.46.34.  .51MABC56535555   MABC62646465L      E 17   MBCY
    . . . . .   . . . . . 12     10792003DL2 28680.05 43883.07  39. 9.39.-119.46.33.  .49MABC56515654   MABC62646565L      E 17   MBCY
    . . . . .   . . . . . 12     03230598DL2 28679.83 43881.91  39.34.28.-119.46.59.  .81MABC56525655   MABC63636465L      E 17   MBCY
    . . . . .   . . . . . 12     00740390DL2 28679.76 43881.43  39.42. 4.-119.46. 6.  .15MABC56315655   MABC62646565L      E 17   MBCY
N  3 9.4 2.7W1 1 9.4 5.812     00090202FL2 28679.66 43880.39  39.42.48.-119.45.53. -.02MABC56505555   MABC63646463L      E 17   MBCY
N  3 9.4 2.5W1 1 9.4 5.812     00060166FL2 28679.60 43879.70  39.42.35.-119.45.52. -.04MABC56525554   MABC63636164L      E 17   MBCY
          0.4 1 6 4            L 00040152DL2 28679.45 43878.87  39.42.19.-119.45.51. -.05MABC15550055   MABC63646564L      E 17   MBCY
          0.3 1 6 4       23   L 00030149DL2 28679.34 43878.55  39.42.12.-119.45.51. -.05MABC56505654   MABC63646564L      E 17   MBCY
           .              23     00000146DL2 28678.77 43877.30  39.41.49.-119.45.52. -.03MABC55515554   MABC63646564L      E 17   MBCY
          5.2 1 6 3       23     00520145DL2 28678.48 43876.77  39.41.40.-119.45.52. -.01MABC55525654   MABC63646564L      E 17   MBCY
          5.1 1 6 3       23     00510145DL2 28678.17 43876.25  39.41.31.-119.45.53.  .00MABC56535555   MABC63646665L      E 17   MBCY
          4.6 1 6 3       23     00460145DL2 28677.40 43874.80  39.41. 5.-119.45.55.  .02MABC55515655   MABC63646566L      E 17   MBCY
          4.4 1 6 2       23     00440144DL2 28676.97 43873.97  39.40.52.-119.45.56.  .03MABC56495655   MABC63656566L      E 17   MBCY
          4.4 1 6 2       23     00440144DL2 28676.97 43873.97  39.40.52.-119.45.56.  .03MABC56495655   MABC63656566L      E 17   MBCY
          4.4 1 6 2       23     00440144DL2 28676.97 43873.97  39.40.52.-119.45.56.  .03MABC56495655   MABC63656566L      E 17   MBCY
          4.4 1 6 2       23     00440144DL2 28676.97 43873.97  39.40.52.-119.45.56.  .03MABC56495655   MABC63656566L      E 17   MBCY
          4.4 1 6 2       23     00440144DL2 28676.97 43873.97  39.40.52.-119.45.56.  .03MABC56495655   MABC63656566L      E 17   MBCY
          3.0 1 6 2       23     00300147DL2 28675.11 43869.14  39.39.29.-119.45.56.  .02MABC565[illegible]54   MABC61656465L      E 17   MBCY
```

Figure 5.3   Typical TDL-711 RDU Display Output

The error analysis process is accomplished in the following manner. The multilateration equations are used to derive actual position of the aircraft in X, Y coordinates, which are then converted to latitude and longitude. The navigator RDU data stream provides Loran-C derived latitude and longitude, cross track deviation (Flight Technical Error -- FTE) and distance to waypoint (DTW) data. From these parameters, and the waypoints which define the approach course, the other error components are calculated:

Given:

LAT_D, LON_D	latitude/longitude derived from the DME data
LAT_L, LON_L	latitude/longitude derived by the Loran-C navigator
FTE	Loran-C Flight Technical Error
DTW_L	Loran-C Distance to Waypoint
LAT_{TO}, LON_{TO}; LAT_{FR}, LON_{FR}	Coordinates of the TO and FROM waypoints

Find:

ΔN, ΔE	Loran-C navigation error in Northing and Easting coordinates
TSCT	Total System Cross Track Error (aircraft position relative to intended course)
ATD	Along Track Distance
NAT, NCT	Loran-C navigation error in Along and Cross Track coordinates

Step 1: Define Course Geometry

From the lat/long of the waypoint pair, find the inbound track bearing (radial)

$$\text{Tan } \beta_T = \frac{LON_{FR} - LON_{TO}}{LAT_{FR} - LAT_{TO}} \text{ Cos } (LAT_{TO})$$

Step 2: Find Northing and Easting Errors

$$\Delta N = LAT_L - LAT_D$$

$$\Delta E = (LON_L - LON_D) \text{ Cos } (LAT_D)$$

(Northing and Easting errors are independent of geometry)

Step 3: Find Track-Related Aircraft Position

$$\text{Tan } \beta_D = \frac{LON_D - LON_{TO}}{LAT_D - LAT_{TO}} \text{ Cos } (LAT_{TO})$$

$$DTW_D^2 = (LON_D - LON_{TO})^2 \text{ Cos}^2(LAT_{TO}) + (LAT_D - LAT_{TO})^2$$

$$TSCT = DTW_D \cdot \text{Sin}(\beta_T - \beta_D)$$

$$ATD = DTW_D \cdot \text{Cos}(\beta_T - \beta_D)$$

Step 4: Find Track-Related Loran-C Position

FTE and DTW_L are given

$$ATD_L^2 = DTW_L^2 - FTE^2$$

Step 5: Compute Track-Related Navigation Errors

FTE is given

TSCT is calculated in Step 3.

$$NCT = TSCT - FTE$$

$$NAT = ATD - ATD_L$$

The relationships among all six error components (including Northing and Easting errors) are illustrated by the following numerical example with associated diagram in Figure 5.4. Assuming the following Northing, and Easting errors:

$\Delta N = 0.01$ nm

$\Delta E = 0.36$

and given that the pilotage error (FTE) is 0.06 nm. on a course bearing of 28° (β_T = 208°), the following errors result:

FTE = 0.06 nm

TSCT = 0.24

NCT = 0.31

NAT = 0.18

All six of the error components are evaluated statistically by computing their mean values and standard deviations according to standard formulas:

mean value of N samples $x_1, x_2, \ldots x_n$

$$\bar{X} = \frac{1}{N} \Sigma x_i$$

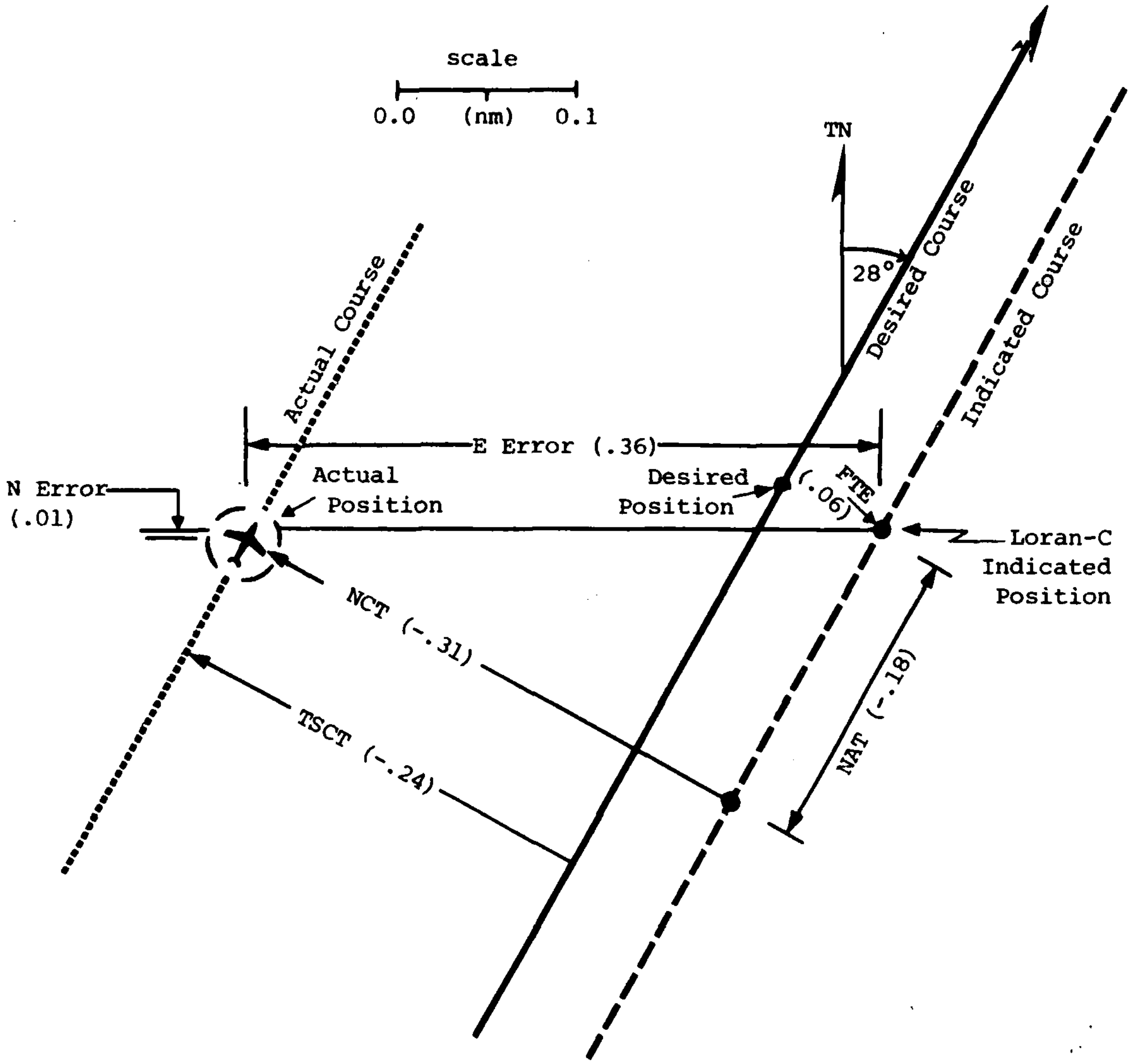


Figure 5.4 Numerical Example of Loran-C Error Geometry

standard deviation of those samples

$$\sigma_x = \sqrt{\frac{\Sigma x_i^2 - N\bar{X}^2}{N - 1}}$$

These values are calculated for each error component on each approach segment flown. Statistics on similar segments are aggregated together using permutations of the above equations. These result in $\bar{X}$, σ_x values which are mathematically equivalent to performing the summations over all of the individual data points concerned.

The error statistics may be interpreted relative to the area navigation performance requirements of FAA Advisory Circular 90-45A. The implications of AC 90-45A requirements on Loran-C operations and performance have been discussed in Section C. 1.2.2.of an earlier flight test report concerning a different Loran-C navigator ("Airborne Evaluation of the Production AN/ARN-133 Loran-C Navigator", Reference 2), parts of which are excerpted in the following paragraphs.

The acceptable means of compliance for demonstrating Loran-C capabilities as an area navigation system suitable for NAS operations are currently delineated in FAA Advisory Circular 90-45A, Appendix A, Section 2 [4]. This advisory circular section is further subdivided into accuracy requirements (2.a), system design requirements (2.b), equipment installation specifications (2.c), and flight manual information requirements (2.d). The data collected during the Loran-C flight testing was primarily applicable to the accuracy requirements for compliance. Therefore, the accuracy requirements of Section 2.a of AC 90-45A are briefly reviewed in the following text. The accuracy criteria set forth in this section of the advisory circular are subdivided into separate requirements for three classes of area navigation system. These classes are:

"2.a (1) 2-D RNAV System using Reference Facility for continuous navigation information."

"2.a (2) 2-D RNAV systems which use VOR/DME information from other than the Reference Facilities."

"2.a (3) 2-D RNAV system not using VOR/DME for continuous navigation information."

Obviously, the Loran-C navigation system belongs in category 2.a (3). The accuracy requirements of this subsection are reproduced in the following paragraphs.

(3) <u>2-D RNAV System not using VOR/DME for continuous navigation information</u>. The total of the error contributions of the airborne equipment (including update, aircraft position and computational errors), when combined with appropriate flight technical errors listed in 2.a(4) below, should not exceed the following with 95% confidence (2-sigma) over a period of time equal to the update cycle:

	Cross Track	*Along Track*
Enroute	*2.5 nm*	*1.5 nm*
Terminal	*1.5 nm*	*1.1 nm*
Approach	*0.6 nm*	*0.3 nm*

(4) 2-D Flight Technical Errors (FTE) when combined RSS with the errors discussed in (1) and/or (a) above determine the Total System error. The Total System error is used by airspace planners and includes the following specific FTE values for determining cross track position accuracies. Values larger than these must be offset by corresponding reduction in other system errors (see Appendix C). No FTE is used in determining the along track accuracy.

Enroute	*±2.0 nm*
Terminal	*±1.0 nm*
Approach	*±0.5 nm*

When the process of calculating the track-related error quantities (FTE, TSCT, NCT, NAT) has been accomplished, the procedures of AC 90-45A Appendix C can be used to combine the error elements into an acceptable error budget. These procedures are based on the assumption that the variable errors from each of the error sources are normally distributed and independent. In this case, the errors may be combined in RSS (root-sum-square) fashion in order to demonstrate compliance. That is, the standard deviations, σ_{FTE} and σ_{NCT} may be combined by taking the square root of the sum of the squares:

$$\sigma_{TSCT} = \sqrt{\sigma^2_{FTE} + \sigma^2_{NCT}}$$

Using this recommended equation and rearranging terms, the implied budget for airborne equipment may be calculated from the values for total system error and FTE listed in Appendix A of AC 90-45A. That is,

$$\text{Required } \sigma_{NCT} = \sqrt{\sigma^2_{TSCT} - \sigma^2_{FTE}}$$

The resulting values for the demonstration of compliance of the Loran-C navigator system have been calculated. These are:

AIRBORNE EQUIPMENT ERRORS (2σ)

	Cross Track (NCT)	Along Track (NAT)
Enroute	1.5 nm	1.5
Terminal	1.1 nm	1.1
Approach	0.3 nm	0.3

The reason that the cross track and along track airborne equipment accuracy requirements are identical is that the FTE error budget values have been removed from the TSCT to derive cross track airborne equipment requirements and by definition from AC 90-45A, "No FTE is used in determining the along track accuracy requirements". As previously noted, the airborne equipment error budget inherently includes errors in Loran-C position due to transmission and propagation errors. In addition, the airborne equipment error budget includes all signal filtering, processing, computational, output and display errors associated with the airborne Loran-C navigator system.

One possible fallacy in the techniques prescribed in AC 90-45A which may be borne out by the test results is that the FTE values specified may be significantly larger than the values measured in the test, since the values specified are based on VOR/DME RNAV system characteristics rather than Loran-C. Furthermore, the RSS technique may not be valid (errors may be correlated). These factors may tend to cause the application of AC 90-45A criteria to Loran-C to be quite conservative.

6.0 OPERATIONAL RESULTS

6.1 TDL-711 PERFORMANCE

A review of the performance of the TDL-711 as a navigator, both as tested in the lab, and as it behaved inflight, is contained in the following sections. This section deals only with the system's abilities to compute positional and guidance information. Section 6.2 and 6.3 deal with operator interactions with the system and navigation accuracy respectively.

6.1.1 Laboratory Performance of the TDL-711

Early performance and operational problems of the TDL-711 when received by the Sierra Nevada Corp. are described in detail in reports produced by that company (for example, see Reference 3). This immediate section shall cover operation of the navigator immediately prior to its installation in the test aircraft. Performance differed at this later time due to software changes provided for the navigator.

The navigator was operated in a bench configuration connected to its antenna mounted outside the laboratory on a suitable ground plane. When initialized, the system would require up to two minutes to lock onto the selected triad and achieve a navigation solution. While it was operated on both the Fallon-Middleton-George (FMG) and Fallon-Middletown-Searchlight (FMS) triads, most bench testing was done using FMG. The location of the lab facility is 39° 39.45'N and 119° 52.16'W. Typically, when using FMG, the navigator would read 39° 39.3'N and 119° 52.0'W. When using FMS, the navigator would read 39° 40.4'N and 119° 52.2'W. Observations of these numbers were made on several different dates. Therefore, consistent biases of -.26 nm North and .12 nm East (FMG), and 0.84 nm North and 0.03 nm East were observed.

The navigator was left in operation for extended time periods on the bench. A characteristic of the system was the periodic occurrence of a loss-of-track condition. This condition, which was typically of short duration ($\sim$30 sec.), would occur with no set pattern, but could occur more than once per hour. The system would light the decimal points as a warning, and reconverge on the lat/lon solution. When Area 2 was selected, the solution was typically as stated above (for FMS). When Area 1 was selected (FMG), a totally erroneous solution was often displayed.

That location was 24° 38.0'N and 106° 27.5'W, which is somewhere in western Mexico. That solution was verified to be the alternate solution on the other side of the F-G baseline. This alternate is illustrated in Figure 6.1. This characteristic, known as "jumping the baseline", should not normally occur when operating distant from the baseline extension.

Immediately prior to installing the system in the test aircraft, the system was evaluated on the bench using the a tenna mounted on the aircraft. No changes to either the acquisition time or the resulting Loran biases were observed in this configuration.

During the bench tests, an operational procedure which disables proper operation of the navigator was discovered. This procedure, which utilizes the diagnostic mode of the navigator, is not a normal flight procedure. However, as discussed in detail in Section 6.2, the keystroke sequence can be inadvertently duplicated in flight and therefore, this creates a potentially serious operational problem. When utilizing the diagnostic mode, the keystroke sequence causes the Course Deviation Indicator to center with the warning flag out of view. Also, proper operation of the RDU data port is disrupted. Proper operation resumes only after reinitialization. This condition was reported to the manufacturer, and the causative program error was found.

6.1.2 Inflight Performance of the TDL-711

This section contains a thorough examination of some of the inflight characteristics of the TDL-711.

6.1.2.1 Operational Behavior

The data for the 24 test approaches was run through a computer program designed to extract certain basic information about the operational behavior of the TDL-711. The computer scan restricted itself to those periods when either the 1-2, 2-3, or 3-4 waypoint pair was selected on the CDU. The data, then, would indicate performance during the actual approaches. The following events were recorded:

1. Start time for the approach (the time at which the 1-2 waypoint pair was first entered indicating the pilot's intent to begin positioning the aircraft for the procedure)

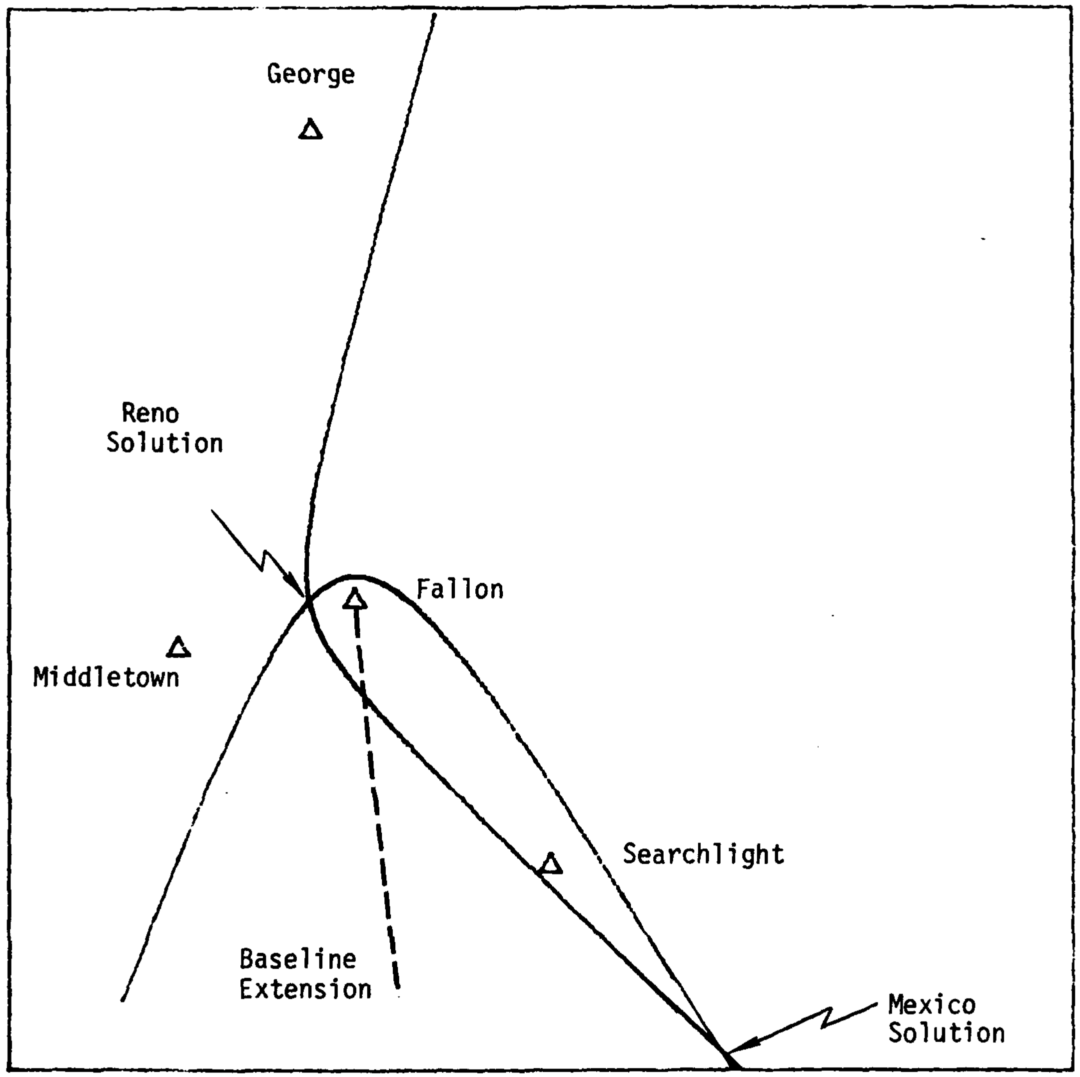


Figure 6.1 Ambiguous Solutions at Reno Using Fallon - Middletown - George

2. Start time of a break in lock (indicated by the illumination of all the decimal points in the CDU display).

3. Stop time of a current break in lock (indicated by the disappearance of all but the decimal points actually in use in the selected display mode).

4. Duration (in seconds) of the break in lock.

5. Stop time of the approach (the time at which some waypoint pair other than 1-2, 2-3, or 3-4 was selected once an approach had begun).

Start and stop times were in total seconds from midnight. Figure 6.2 shows all 24 approaches plotted from the results of the computer scan. Each approach location and start time, along with the selected Loran-C triad, appears to the left of center. To the right of center is a line representing elapsed time from start approach to stop approach. Each pair of short vertical lines (when present) indicates the start and stop of a break in lock and their separation indicates duration.

Neither the number of breaks in lock during an approach nor the likelihood of single or multiple occurrences shows any discernible overall pattern.

A break in lock did take place in roughly the same area (about 11 nm from the threshold) in each of the three approaches to Reno International Airport, although the exact cause of this problem is not clear. It may be related to the location of the Sparks NDB on the approach centerline. The approximity of a 50 KW AM radio station broadcasting on 720 KHz 1.5 nm southwest of the NDB may also have contributed to the occurrences, but the exact radiation pattern from this high power source is unknown at present and its effects cannot be predicted. In addition, since no controlled, experimental data was collected on aircraft antenna sensitivity patterns and resonant frequencies, the effects of antenna sensitivity cannot be excluded as a causal or contributing factor. There was no indication from the signal to noise ratios (SNRs) available from the navigator of any significant interference, but no independent measurement of noise was made. The TDL-711 itself was the only data source.

One break in lock shown in Figure 6.2 was confirmed to have been caused by a temporary station outage. This is the one identified as "South Lake Tahoe 9:9:18 (FMS)" in the figure. Circumstances and documentation concerning this are contained in Appendix C.

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WEST COAST LORAN-C FLIGHT TEST.(U)

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UNCLASSIFIED FAA-RD-80-28 NL

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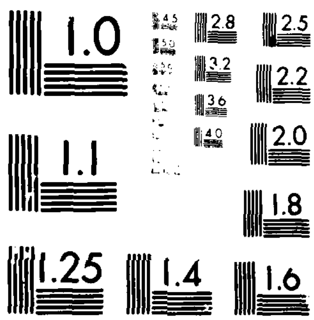

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963-A

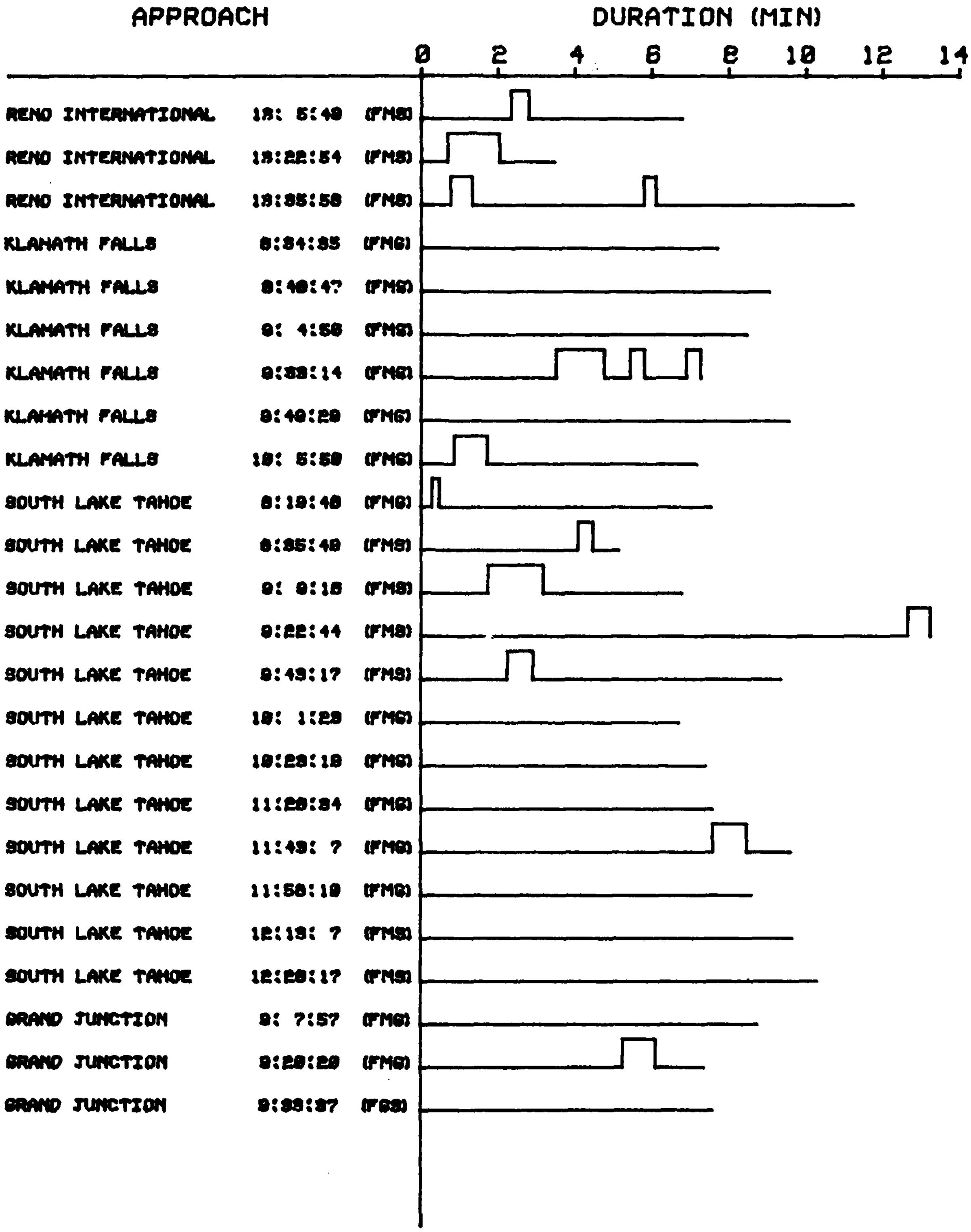

Figure 6.2 Occurrences of Breaks in Lock During West Coast Loran-C Flight Test

The entire set of approaches represents a total of 11922 seconds of elapsed time (198.7 minutes). The total duration of all the breaks in lock was 650 seconds (10.8 minutes). Table 6.1 shows that 5.5 percent of the total approach time was spent in a break in lock condition. Since 12 of the approaches contained breaks in lock the chance of at least one break lock in any approach was 1 in 2. Table 6.2 shows that a total of 15 breaks in lock occurred during the portions of the 24 approaches in the sample, or .625 occurrences per approach.

Table 6.1 Break in Lock Duration vs Total Time

TOTAL TIME (secs)	TOTAL BREAKS IN LOCK (secs)	BREAK IN LOCK %
11922	650	5.5

Table 6.2 Breaks in Lock Per Approach

NO. OF APPROACHES	NO. OF BREAKS IN LOCK	BREAKS IN LOCK PER APPROACH
24	15	.625

The longest single break in lock lasted 88 seconds, the shortest lasted 12 seconds. The mean duration was 43.33 seconds with a one σ deviation of 23.88 seconds (see Table 6.3).

Table 6.3 Statistical Analysis of Breaks in Lock

TOTAL DURATION (secs)	NO. OF BREAKS IN LOCK	MEAN DURATION (secs)	σ (secs)
650	15	43.33	23.88

6.1.2.2 Time Difference to Latitude/Longitude Conversion Model

The recording of time difference data, Loran-C latitude and longitude, and the computation of RAPPS position in latitude and longitude provided an opportunity to evaluate the accuracy of the time difference to latitude/longitude conversion process and to analyze potential Loran-C accuracy improvement through the use of improved electromagnetic propagation models.

The procedure that was used to evaluate the time difference to latitude/longitude conversion process of the TDL-711 navigator is shown by the block diagram in Figure 6.3. Station- and triad-specific data such as latitude/longitude of the transmitter, coding delay, and baseline length in microseconds are stored for use by the procedure. The procedure is initiated by providing the actual time difference values and an estimated latitude/longitude position of the aircraft. This estimated position must be sufficiently close to the actual aircraft position to prevent convergence to the alternate position if one should exist. Usually a position estimate within 50 to 100 nautical miles of the actual position is sufficient. Next, estimated distance to station values are computed for a spheroidal earth model. The procedure for this computation was taken from FAA Advisory Circular 90-45A, Appendix J. However, earth radii used in the procedure are taken from Reference 8, which uses the World Geodetic System - 1972 Datum. These values are:

equatorial radius (a) = 6,378,135.000 meters
polar radius (b) = 6,356,750.500 meters
flattening (f) = (a-b)/a = 1/298.26

Once the distance to the station is determined the propagation time delay for the distance traveled is computed. The primary factor delay is found by dividing the distance traveled by the speed of light at the earth's surface for a standard atmosphere. The speed of light values were taken from Reference 9 by dividing the speed of light in free space (299.792458 meters/μ sec) by the surface index of refraction for the standard atmosphere (1.000338). The speed of propagation at the surface of the earth is 299.6911624 meters/μ second.

A block was provided in the computation procedure for using a secondary propagation factor refered to as t_c in NBS Circular 573[4]. Initially, this factor was set to zero to produce results that agreed closely with the TDL-711 latitude/longitude values. Later, secondary factors representative of several ground conductivities were used for the purpose of attempting to reduce the Loran-C bias error at the several test locations.

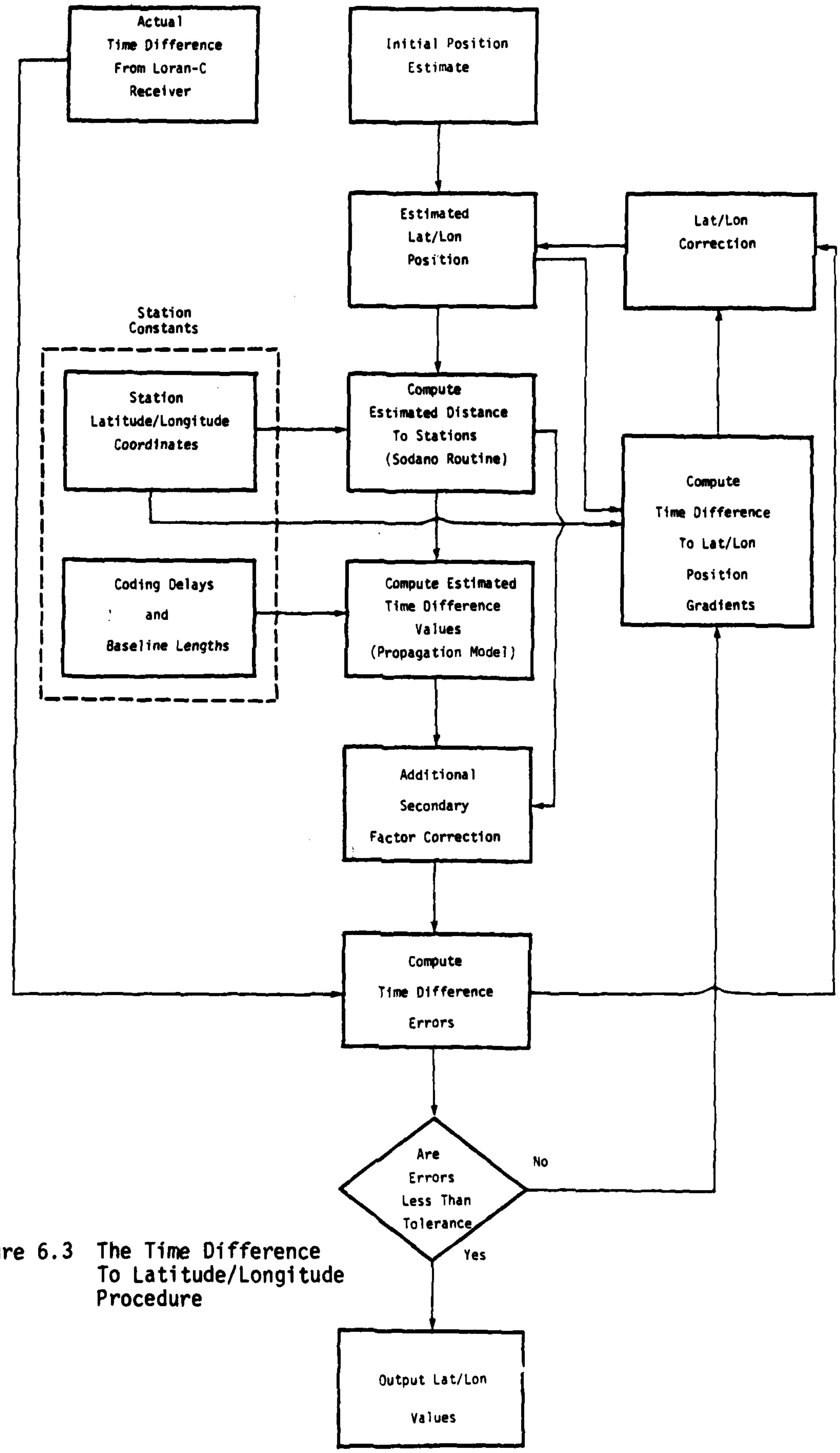

Figure 6.3 The Time Difference To Latitude/Longitude Procedure

Once the estimated propagation times are computed the appropriate coding delay and baseline length factors are added to produce estimated Loran-C time difference values. These values are compared to the actual time differences recorded by the Loran-C receiver and time difference errors are determined. These time difference errors are tested against an error tolerance value. In this procedure the criteria used in the test is:

$$\left|\Delta TD_A\right| + \left|\Delta TD_B\right| \leq 0.01 \ \mu s$$

If the test is positive, the estimated latitude/longitude value is accepted as the actual Loran-C derived aircraft position. If the test is negative, latitude and longitude corrections are computed and added to the estimated position and the entire procedure is repeated until convergence is obtained.

The latitude and longtiude corrections are computed from gradients of the spherical distance equation

$$\cos \theta = \sin(L_S)\sin(L_p)+\cos(L_S)\cos(L_p)\cos(\lambda_p-\lambda_S)$$

and the propagation time equation

$$\tau = \frac{R_e\theta}{C}$$

where

θ = central angle at the center of the earth

L_S = latitude of the station

λ_S = longitude of the station

L_p = latitude of the aircraft (estimated)

λ_p = longitude of the aircraft (estimated)

R_e = radius of the earth

C = velocity of electromagnetic propagation

from which is obtained:

$$\frac{\Delta\tau_{SP}}{\Delta L_p} = GRLA_{SP} = \left(\frac{R_e}{C}\right)\frac{\cos(L_S)\cos(\lambda_p-\lambda_S)\sin(L_p)-\sin(L_S)\cos(L_p)}{\sin \theta}$$

$$\frac{\Delta\tau_{SP}}{\Delta\lambda_p} = GRLO_{SP} = \left(\frac{R_e}{C}\right)\frac{\cos\ (L_S)\cos(L_p)\sin(\lambda_p-\lambda_S)}{\sin \theta}$$

from which the total differential may be written

$$\Delta\tau_{SP} = GRLA_{SP} * \Delta L_P + GRLO_{SP} * \Delta\lambda_P$$

Applying the total differential to the time difference measurements and letting M represent the master station and with A and B representing the two secondaries, the following matrix gradient equation is obtained:

$$\begin{bmatrix} \Delta\tau_A \\ \Delta\tau_B \end{bmatrix} = \begin{bmatrix} GRLA_{AP}-GRLA_{MP} & GRLO_{AP}-GRLO_{MP} \\ GRLA_{BP}-GRLA_{MP} & GRLO_{BP}-GRLO_{MP} \end{bmatrix} \begin{bmatrix} \Delta L \\ \Delta\lambda \end{bmatrix}$$

or

$$\begin{bmatrix} \Delta\tau_A \\ \Delta\tau_B \end{bmatrix} = \begin{bmatrix} M \end{bmatrix} \begin{bmatrix} \Delta L \\ \Delta\lambda \end{bmatrix}$$

where M represents the 2X2 gradient matrix. The incremental change in latitude and longitude can be found by solving the matrix equation and obtaining

$$\begin{bmatrix} \Delta L \\ \Delta\lambda \end{bmatrix} = \begin{bmatrix} M \end{bmatrix}^{-1} \begin{bmatrix} \Delta\tau_A \\ \Delta\tau_B \end{bmatrix}$$

These values of latitude and longitude correction are applied to the estimated latitude/longitude position and the procedure is repeated until convergence in obtained.

6.1.2.2.1 Application of the Model

The time difference to latitude/longitude conversion model was used for two purposes. The first application was the evaluation of the conversion accuracy of the TDL-711 navigator. For this purpose time difference values recorded from the RDU data bus were used as input to the coordinate conversion model and the model output was compared to the Loran-C latitude/longitude values recorded from the RDU data bus.

The second application of the model was for an analysis of the propagation model used in the TDL-711 navigator. In this application the model was modified to provide time difference error outputs when RAPPS-derived latitude/longitude values were used as position inputs.

The block diagram for this procedure is shown in Figure 6.4. Other than the input/output values, a major difference in this procedure as compared to that shown in Figure 6.3 is the use of the secondary propagation factors. Equations for these propagation factors were derived from the theoretical data found in NBS Circular 573[4]. Secondary factors were computed from an equation of the form:

$$\tau_C = A/D+B+C*D$$

where

τ_C = secondary factor propagation delay

D = distance from station to aircraft

A,B,C = constants derived from theoretical delay values

The constants A,B, and C are obtained by least mean square curve fitting methods using data found in NBS 573. One set of constants is used for distances less than 100 statute miles, and another set is used for distances greater than 100 miles. In the 100 mile area a blending function is used to avoid discontinuous corrections. In all, eight conductivity values were used in the evaluation. These values are shown in Table 6.4.

Table 6.4 Conductivity Values

CASE NUMBER	CONDUCTIVITY (σ) (mhos/meter)	RELATIVE PERMITTIVITY (ε_R)	TYPICAL AREA
1	0.0000	15	
2	0.0001	15	Extremely poor soil, cities
3	0.0005	15	Permafrost, snow covered mountains
4	0.0010	15	Poor rocky soil
5	0.0020	15	
6	0.0050	15	Fresh water, good soil
7	0.0500	15	
8	5.0000	15*	Seawater

*Relative permittivity for seawater is about 80 but delay is not strongly influenced by permittivity

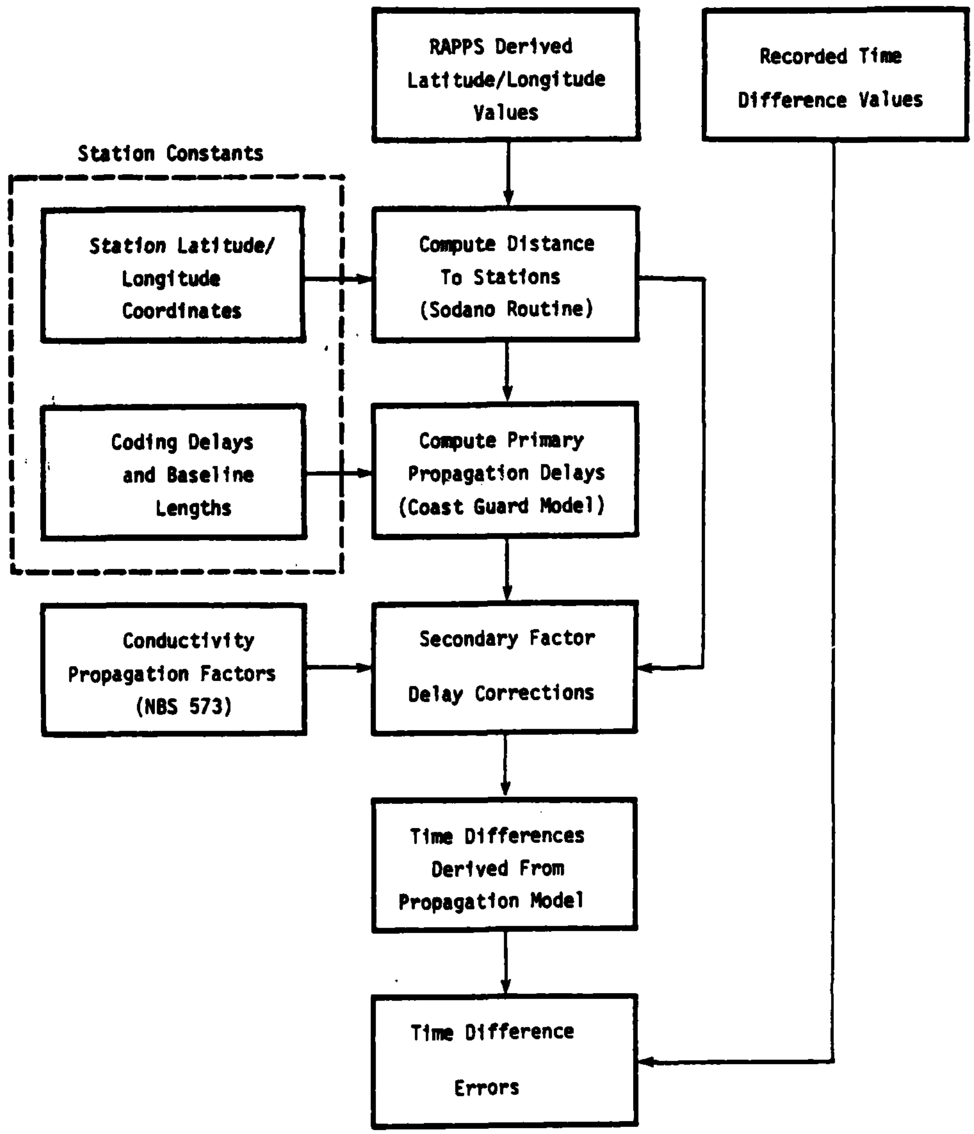

Figure 6.4 The Time Difference Error Analysis Procedure

In addition to the conductivity analysis an analysis of time difference error reduction by reducing the value used for propagation velocity was performed. The details of this analysis are described in Section 6.1.2.2.3.

6.1.2.2.2 Evaluation of the TDL-711 Coordinate Conversion

The coordinate conversion procedure depicted in Figure 6.3 was used to evaluate the time difference to latitude/longitude conversion capability of the TDL-711. Time difference values recorded from the RDU data bus were input into the procedure described in Figure 6.3 and the latitude/longitude values output from the procedure were compared with latitude/longitude values in the RDU data output which were computed by the navigator. No correction for secondary factor delay was used in this analysis.

The analysis revealed three different outcomes. First, for the majority of data points the agreement between the analysis procedure and the TDL-711 latitude/longitude position was very acceptable for air navigation purposes. A summary of the error statistics for these points is presented in Table 6.5. The aggregate error for five locations totaling 737 data points was:

	Mean Error	Standard Deviation
Latitude	71 feet	86 feet
Longitude	-32 feet	29 feet

These values were considered to be in excellent agreement considering the complexity of the coordinate conversion process.

Table 6.5 Latitude/Longitude Coordinate Conversion Errors

Location/Triad	N No.Points	$\overline{X}_L$ Mean Lat	σ_L St Dev Lat	$\overline{X}_\lambda$ Mean Lon	σ_λ St Dev Lon
RENO/FMS	71	94'	143'	-42'	31'
STEAD/FMG	22	60'	35'	-11'	24'
STEAD/FMS	19	142'	25'	- 8'	24'
KLAMATH/FMG	279	1'	40'	-28	22'
TAHOE/FMS	219	104'	57'	-30'	33'
TAHOE/FMG	90	149'	56'	-53'	28'
GJT/FGS	37	149'	31'	-27'	28'
TOTAL	737	71'	86'	-32'	29'

However, a second outcome was observed on several occasions during the tests. The navigator-calculated position would suddenly, within a few six second output cycles, jump to a location several hundred miles from the actual aircraft position. In each instance examination of the time difference data revealed no significant jumps, discontinuities, or variations, only jumps in navigator position. Time difference values calculated from the position indicated by the navigator RDU latitude/longitude output showed very good agreement with the RDU output time differences. Thus the navigator position had jumped to the alternate latitude/longitude solution where the Loran-C lines of position cross a second time.

The third outcome that was observed in the coordinate conversion process happened at Klamath Falls when the Fallon-Middletown-Searchlight triad was used. Klamath Falls is located near the baseline extension of the Fallon-Searchlight station pair. For this reason the triad would not ordinarily be used for navigation in this area due to the proximity to the baseline extension. However, in some instances, the pilot or navigation set may revert to an inappropriate triad during a station outage or by an unfortunate choice of stations. For this reason it was desirable to evaluate the system performance under such circumstances.

At Klamath Falls, using the FMS triad, the navigator never converged upon a latitude/longitude solution. Analysis of the RDU time difference data and the expected time difference values on or near the baseline extension clearly indicated the reason for the failure to converge.

Using the TDL-711 propagation model on the baseline extension produces a maximum expected time difference value for the Fallon-Searchlight pair of 43933.67 μs. A greater time difference value produces a situation wherein the navigator cannot find a latitude/longitude position that will produce the necessary time difference value. In the RDU data output it was observed that all of the time difference values from the Fallon-Searchlight pair exceeded 43936 μs. Therefore, convergence was impossible with the propagation model used in the TDL-711. The navigator propagation model failed to account for more than 3 μs of delay. This fact, along with the observance of significant bias errors, led to an analysis of the possibility of improving the propagation model.

6.1.2.2.3 Analysis of Propagation Models

For this analysis the computational procedure depicted in Figure 6.4 was used. This procedure requires the use of positional data computed by the RAPPS system and time difference values recorded from the RDU data bus. First, a carefully selected subset of the RAPPS position data was utilized. In order to be assured of accurate position data from RAPPS, only points where at least three beacons were being received were used. In addition, it was required that the DME distances from the beacons agree to within .03 nm (56 meters).

First, the RAPPS data were applied to the procedure that is representative of the TDL-711 propagation model which used no secondary propagation factor terms. The results are shown in Table 6.6. These results indicate that very significant mean time difference errors exist at many of the five flight test locations. These data are plotted as a function of distance to the missed approach point in Appendix B. Three typical plots are shown in Figures 6.5, 6.6 and 6.7. The Searchlight-Fallon and George-Fallon time difference data indicate that the errors are quite repeatable but that they do tend to vary with distance to the waypoint. The Middletown-Fallon data, on the other hand, exhibits a less repeatable pattern, but the overall variation along the approach is about the same as the other two plots. A possible explanation for these characteristics is the rugged terrain over which the signal from Middletown must travel. The effect of terrain upon the LF signal has been noted and analyzed by several researchers[5,6,7].

Next, secondary factor corrections were introduced into the computed time difference procedure shown in Figure 6.4 using the curve fit equations described in Section 6.1.2.3. All eight values of conductivity were evaluated. The results of this analysis in terms of mean time difference error is shown in Table 6.7. The figure of merit which was used for evaluating propagation model effectiveness was the root-mean-square (RMS) value of the fourteen mean time difference errors at the five locations. It is apparent that all conductivity values produced correction factors that reduced the RMS mean time difference error with the values for .0001 and .0050 mhos/meter yielding minimums. A value of .0001 mhos/meters is very low and not generally considered representative of conductivities found in the western areas of the country. The value of .0050 mhos/meter

Table 6.6 Summary of Time Difference Errors (microseconds)

STATION PAIR	GEORGE-FALLON			MIDDLETOWN-FALLON			SEARCHLIGHT-FALLON		
LOCATION	N No. Points	$\overline{X}$ Mean TD	σ Std. Dev.	N No. Points	$\overline{X}$ Mean TD	σ Std. Dev.	N No. Points	$\overline{X}$ Mean TD	σ Std. Dev.
TAHOE	122	2.28	0.35	238	0.44	0.50	116	2.90	.53
STEAD	7	4.26	0.40	15	2.54	1.00	8	3.12	.23
RENO	X	X	X	55	0.24	0.45	55	3.11	.23
GRAND JUNCTION	74	1.94	0.29	42	2.29	0.03	32	-1.37	.14
KLAMATH FALLS	161	0.62	0.69	215	0.94	0.48	54	3.35	.09

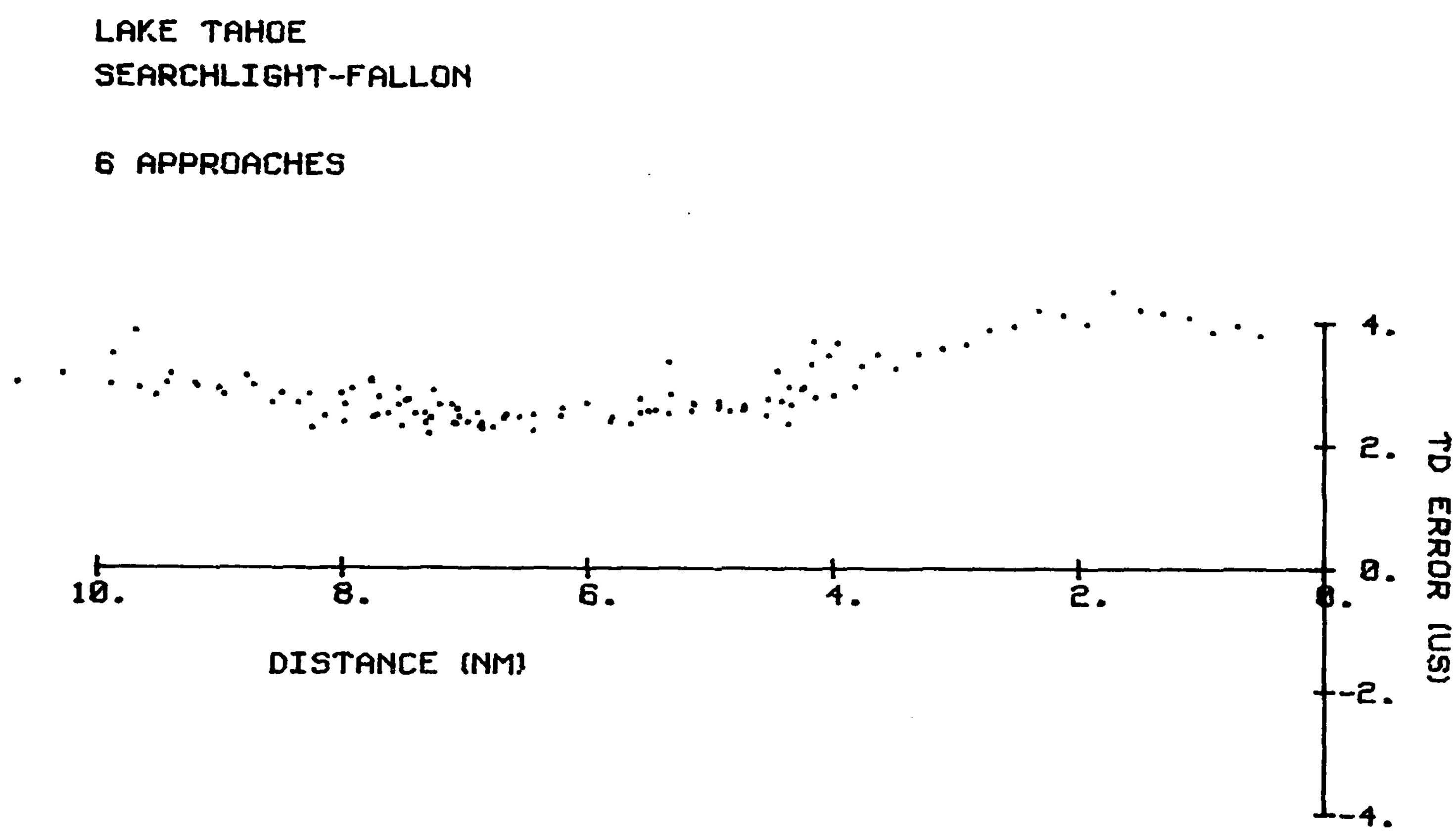

Figure 6.5 Time Difference Error at Lake Tahoe for the Searchlight-Fallon Stations

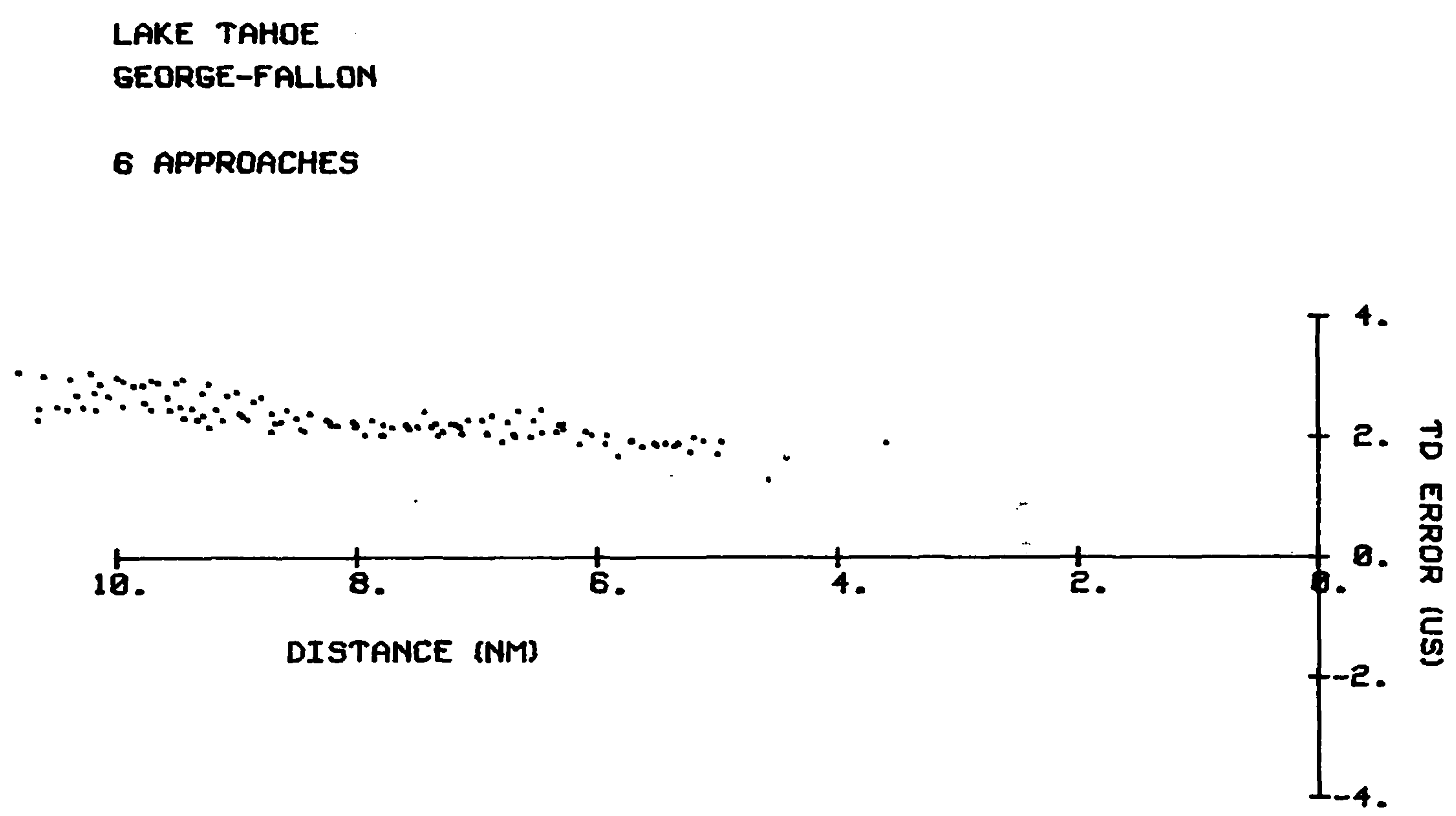

Figure 6.6 Time Difference Error at Lake Tahoe for the George-Fallon Stations

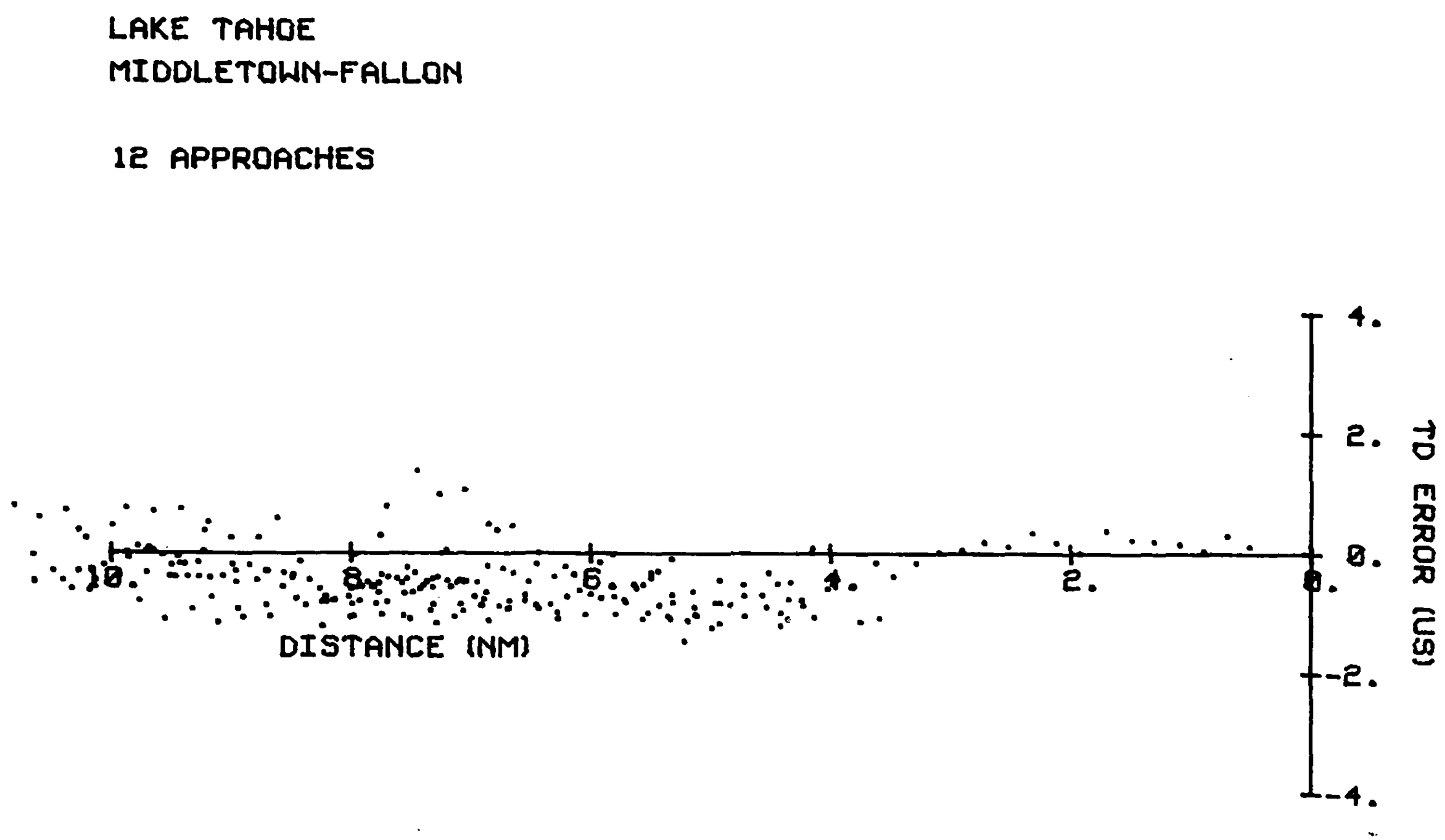

Figure 6.7 Time Difference Error at Lake Tahoe for the Middletown-Fallon Stations

Table 6.7 Conductivity Corrected Mean Time Difference Errors (Microseconds)

LOCATION	Un-corrected	CONDUCTIVITY ASSOCIATED WITH THE CORRECTION FACTOR (mho/meter)							
		0.0000	0.0001	0.0005	.0010	.0020	.0050	.0500	5.0000
Station Pair: George-Fallon									
Lake Tahoe	2.28	-0.96	-1.44	-2.80	-2.64	-2.35	-1.39	0.08	0.73
Stead	4.26	1.21	0.59	-0.80	-0.57	-0.19	0.79	2.25	2.89
Reno	ND	ND	ND	ND	ND	ND	ND	ND	ND
Grand Junction	1.94	0.21	0.08	-0.21	-0.17	-0.12	0.24	0.85	1.13
Klamath Falls	0.62	-0.17	-0.25	-0.50	-0.49	-0.45	-0.24	0.09	0.24
Station Pair: Middletown-Fallon									
Lake Tahoe	-0.44	-0.88	-1.06	-1.47	-1.36	-1.23	-1.03	-0.75	-0.64
Stead	2.54	1.84	1.46	0.87	1.06	1.30	1.64	2.11	2.30
Reno	0.24	-0.54	-1.01	-1.65	-1.42	-1.13	-0.75	-0.23	-0.01
Grand Junction	2.29	0.85	0.73	0.49	0.52	0.56	0.87	1.38	1.61
Klamath Falls	0.94	0.93	0.92	0.92	0.92	0.92	0.92	0.93	0.93
Station Pair: Searchlight-Fallon									
Lake Tahoe	2.90	0.97	0.61	-0.48	-0.36	-0.12	0.55	1.54	1.97
Stead	3.12	0.79	0.22	-1.01	-0.80	-0.45	0.37	1.57	2.09
Reno	3.11	0.79	0.16	-1.10	-0.85	-0.46	0.38	1.59	2.12
Grand Junction	-1.37	-0.59	-0.53	-0.37	-0.39	-0.42	-0.59	-0.87	-1.00
Klamath Falls	3.35	0.81	0.58	-0.03	0.02	0.12	0.72	1.70	2.14
RMS	2.41	0.91	0.81	1.17	1.05	0.93	0.85	1.33	1.64

ND - No Data

reduced the RMS mean time difference error by 65% over the uncorrected data obtained from the propagation model used in the TDL-711.

One empirical method of reducing the time difference error was also analyzed. The method that was developed used a slower primary propagation value and no secondary correction factor. In essence this method used an empirically derived value for the speed of signal propagation. Assume that the primary signal travels a distance D in a time τ_0 with a speed v_0. Then

$$\tau_0 = D/v_0$$

A slower propagation velocity v, will then produce a longer propagation time τ_1 where

$$\tau_1 - \tau_0 = D\left(\frac{1}{v_1} - \frac{1}{v_0}\right) = \frac{v_0 - v_1}{v_0 v_1}$$

let $\Delta v = v_0 - v_1$

and the difference in propagation time becomes

$$\tau_1 - \tau_0 = \frac{D\Delta v}{v_0(v_0 - \Delta v)} \approx \frac{D\Delta v}{v_0^2} \quad \text{for small } \Delta v$$

and let $K = \dfrac{\Delta v}{v_0^2}$

From the flight test data a value of K was determined which minimizes the mean square time difference error. The mean square error (MSE) may be written:

$$MSE = \frac{1}{N} \sum_N e_i^2 = \frac{1}{N} \sum_N (\tau_i - \Delta D_i K)^2$$

where $\sum_N$ represents the sum over the total number N of time difference errors

e_i = the error in the i^{th} time difference after the correction factor has been applied

τ_i = the error in the i^{th} time difference before the correction has been applied

ΔD_i = the distance difference between the two stations forming the Loran-C line of position (secondary distance-master distance)

In order to minimize the MSE the derivative is taken and set to zero

$$\frac{d(MSE)}{d\ K} = 0 = 2\sum_N (\tau_i - \Delta D_i K)*(-\Delta D_i)$$

or

$$2\sum_N (\Delta D_i{}^2 * K) = 2\sum_N (\tau_i * \Delta D_i)$$

solving for K

$$K = \frac{\sum_N (\tau_i * \Delta D_i)}{\sum_N \Delta D_i{}^2}$$

The fourteen values for τ_i from the uncorrected column of Table 6.7 were used to determine K. Values of ΔD_i were computed from distance difference data determined from spherical distances from the airports used in the tests to the appropriate Loran-C transmitter station. From these data the value for K was calculated to be:

$$K = .009465\ \mu s/\text{nautical mile}$$

This value of K produces an RMS error of .83 microseconds which is very consistent with that found by using a conductivity correction of .0050 mhos/meter. The resulting propagation velocity is

$$v_1 = 299.23214\ \text{meters}/\mu s$$

At distances greater than 500 statute miles from the transmitter the additional delay found from the empirical method is nearly identical to the delay found using a conductivity of .0050 mhos/meter, (approximately 4.2 microseconds). At shorter distances the empirical method produces delays that are less than the conductivity method by about 0.5 microseconds.

Either propagation correction method, the secondary factor correction or the empirical velocity of propagation reduction method, could be easily implemented into any navigator system design. It should be noted that the values found in these analyses were limited to only a very few (fourteen) data points. Also, all of the propagation paths were over land and fresh water areas. Regions where part of the path is over land and part is over seawater were not tested at all. Data from a much broader sample of

locations, including some seawater paths and mixed land and seawater paths, are needed before definitive propagation models can be established.

6.2 PILOT INTERACTION WITH THE TDL-711

This section will deal with the practical operation of the TDL-711 RNAV/Loran-C system. The pilot's interface with the receiver processor is through the Control Display Unit (CDU).

6.2.1 Data Entry and CDU Manipulation

Data entry is straightforward with the TDL-711. Once the rotary data selector switch has been set for the intended operation, the keyboard entry operation is simple enough and as each entry progresses it is displayed in the upper left or right windows. Perhaps the single most annoying CDU problem during the test was that the keys, if depressed with an off-center pressure, would stick down. The only evidence of malfunction would be that subsequent key entries would produce no result. The cause of this sticking appeared to be that the edges of the keys were ridged parallel with the face and any off-center pressure during entry could jam those ridges against the edge of the faceplate opening for that key. To free it from the opeing, one needed only to depress the key slightly. More often than not, however, this resulted in a double entry, which then required a clearing of the entire entry and a restart.

Although the pilot did not operate the system during the test approaches because of its placement in front of the copilot's seat, it could be a serious distraction for a pilot alone, especially if the key sticking and double entry occurred at the end of a latitude, longitude, or time difference entry. The additional time and the distraction necessary to re-enter information, and continue flying the airplane, perhaps under instrument conditions, could well increase the probability of, and opportunity for, blunders.

In general, the CDU behaved as the instruction manual said it would. Tactile and aural feedback during data entry or manipulation was good. There was a definite feeling of bottoming out accompanied by a clearly audible click when a key was sufficiently depressed. The data entry

sequences were logical and clear. The RNAV features of the system were very useful during the approaches.

The manual, rather than automatic, leg change feature did not present a problem. The command sequence was simple and quick and the processor swiftly produced the information for the next leg. Another, and potentially more serious, problem with the -711 revealed itself during the tests. The processor has a diagnostic mode through which the operator can use the CDU to call up such information as signal-to-noise ratios (SNRs), envelope numbers, track status, etc.

Unfortunately, an internal design problem caused the processor, in either mode, to use for its diagnostic activity memory locations containing the navigation computations. As a result, the navigation information was overwritten. The only outward sign of this chain of events was that the CDI needle centered. However, no CDI NAV flag appeared.

The techniques for accessing this data on the CDU are not in the TDL-711 Operator's Manual but are in the TDL-711 maintenance manual. To enter the diagnostic mode, the operator select the OFST/VAR position on the rotary data selector switch and press the LEG CHG key or the POS HOLD key for the address or write modes, respectively. While it is true that the average user might have little need to use the diagnostic mode, he could however, enter it inadvertently, with potentially serious operational results.

For example, if a pilot using the -711 were to have moved his rotary selector to OFST/VAR to check which magnetic variation the processor was using in its calculations, and soon after arrived at a waypoint on his route and depressed the LEG CHG switch without repositioning the rotary data selector he would inadvertently have entered the diagnostic mode. Any further keystrokes would cause the processor to begin analyzing those entries and the CDI would center, showing the pilot the potentially false information that he was on course. The pilot might not recognize the problem until it was too late.

Even if the memory use overlap problem were solved and navigation calculations could continue uninterrupted, the inadvertent entry into the diagnostic mode and the unexpected results and symbols which might

appear as a result, would be both distracting and disconcerting to the average user. Coupled with marginal weather and/or terrain considerations, confidence in the system would surely be degraded.

Two considerations are suggested by this scenario. First, the software design should be changed to protect those memory locations containing navigation data and the precaution taken to activate the CDI NAV flag if that data should be overwritten. Second, the technique for calling up the diagnostic modes should be changed to one that cannot be duplicated by using a sequence of normal commands.

The problem with the alphanumeric keys sticking down (often creating a double entry when the key was pressed again to free it) illustrated the operational improvement that would result from the capability to erase the last key stroke without clearing the entire entry, a feature not available on the -711.

The CDU used in this test program rhythmically blinked all the lights and displays on the unit whenever it was on and navigating. The blinking appeared to coincide with the updating cycles of the processor. There is, however, no mention of this behavior in the instruction manual.

The machine, at first, appeared to be malfunctioning. Afterward, when the processor had shown itself to be working properly, the operator came to ignore the blinking. Unfortunately, the processor's warning to the operator that navigation has entered the non-standard, master-independent mode is blinking decimal points —— a signal that could be missed by an operator already conditioned to ignore just such an indication.

6.2.2 Use of the TDL-711 System for Approaches

In contrast to the approach characteristics (as seen in the CDI) of VOR/DME and ILS, the Loran tracking information is noticably smoother and more subtle. Multipath-generated, side to side needle excursions were absent and, as a result, a different pilot technique was necessary to make good use of the information. For example, a slight movement of the needle from center was in fact showing a slight drifting of the aircraft from the desired course track. Once the pilot realized that

the increased steadiness was the rule rather than the exception, it was possible to fly the approach (given good Loran signal characteristics) with the CDI needle centered much more of the time, and with impressive repeatability. The sureness of the guidance would be very useful during approaches under instrument conditions since the Loran guidance through the -711 is free from the "windshield-wiper" needle excursions characteristic of VOR/DME based navigation systems.

The accuracy and reliability of the distance to waypoint calculations free the pilot from the sometimes confusing characteristics of conventional DME representations which can, due to mechanical or signal anomolies (or both), produce DME readings which change suddenly during an approach and which can introduce an element of ambiguity at critical points during an approach procedure. Accurate and reliable distance to waypoint information is another essential input for pilot confidence in the navigation system.

CDI needle movement was negligible during shifts to the next waypoint pair. Test data shows that it took roughly 6 to 12 seconds for the navigation computer to make the change to a new waypoint pair and that during the changeover, course and distance to waypoint continued to be calculated based on the old waypoint pair. The leg change procedure was simple and clear, and the disruption to the pilot's instrumentation was minimal.

During the test, the TDL-711 was most often operated in the DIST/BRG mode which gave the pilot his most useful information during the approach. The present position mode was used occasionally to double check the navigator's accuracy and to check on the navigator's progress toward an accurate position solution after first being powered-up or during its recovery after breaking lock.

The estimated time enroute/groundspeed mode is also useful inflight as a short term planning tool. However the track angle error, track angle, cross track distance, and desired track angle information provided by the system were never selected and are of little use to the pilot, either enroute or during an approach. The CDI, coupled with the information provided in the distance to waypoint/bearing to waypoint mode, gives the pilot his most usable navigation picture.

6.3 SYSTEM ACCURACY

This section contains a detailed analysis of the accuracy of the Loran-C navigator, the Loran-C signals, and pilot performance. The following five subjects are discussed:

1) The individual plots of aircraft track and Loran guidance on each approach (the total set of plots are included as Appendix A).
2) Statistical analysis of approaches to five airports (non-area-calibrated mode) operating with different Loran-C triads.
3) Statistical analysis of area-calibrated approaches conducted at two airports.
4) A summary of the analytical investigation of the coordinate conversion capabilities of the Loran-C navigator contained in Section 6.1.
5) Overall accuracy assessment and the implications on approach and enroute airspace requirements.

Appendix A contains the entire set of 26 approach plots. Each plot shows the actual aircraft track (Total System Cross Track - TSCT) error as a dashed line, and Loran-C navigator indicated position (Flight Technical Error - FTE) as a solid line. An example is reproduced here as Figure 6.8, an approach to South Lake Tahoe runway 18. Appendix A also contains the aggregated data plots for each of the five airports. These are presented in sets of three plots each. The first is a composite of the TSCT profiles of all the flights flown at a given airport. The second is a similar composite showing the indicated aircraft position (FTE) data. Both of the above sets of curves are identical to the curves on the individual approach plots. The third composite plot shows the values of Navigation Cross Track (NCT) error, which is the difference between TSCT and FTE. As an example of these composite plots Figures 6.9 through 6.11 are presented. These show the composite results of 24 of the 26 total approaches. The Reno, Stead approaches are not included since they were not conducted as full, three - waypoint approach procedures. Included are the five area calibrated approaches flown at South Lake Tahoe and Grand Junction.

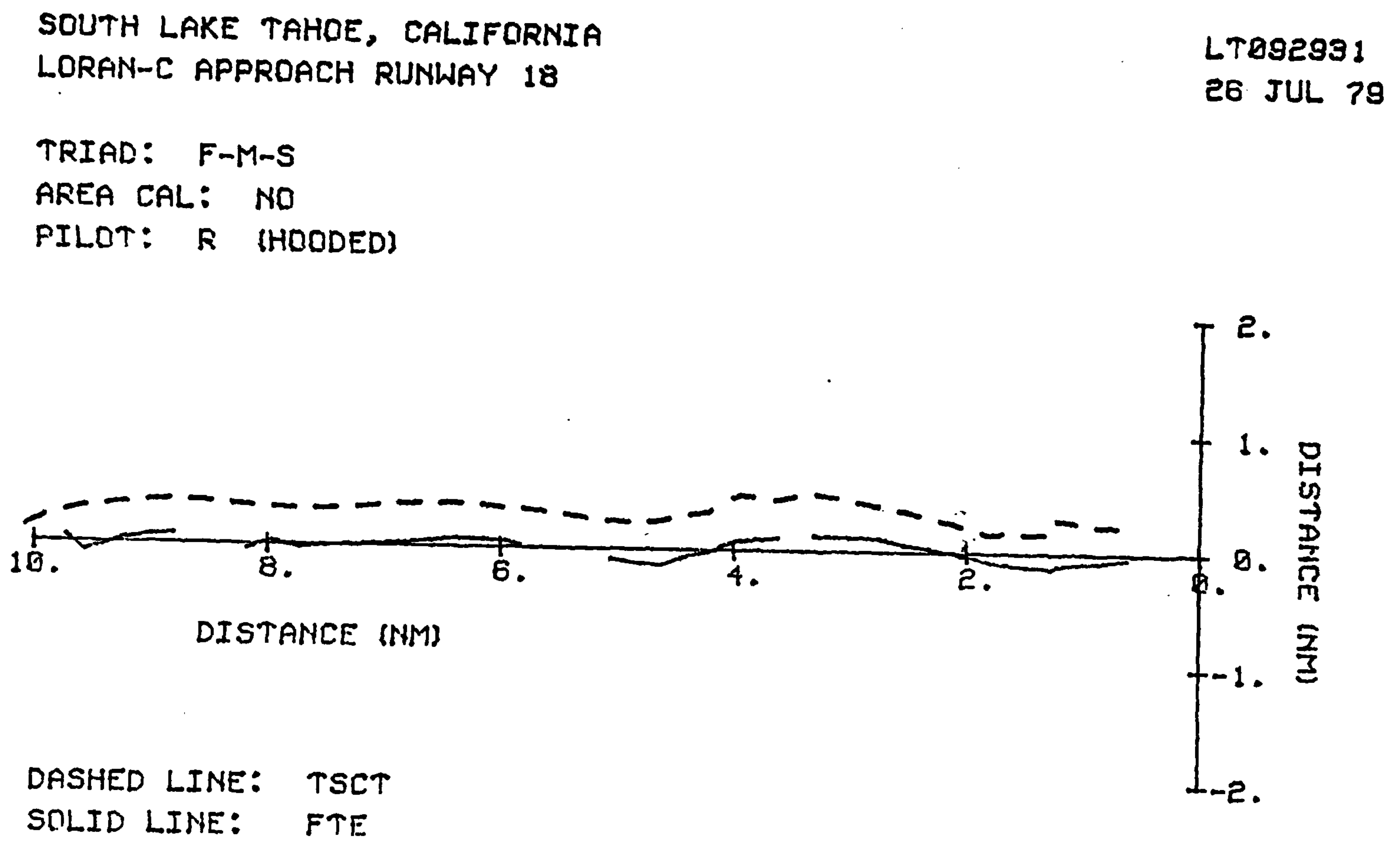

Figure 6.8 South Lake Tahoe, California Loran-C Approach Runway 18

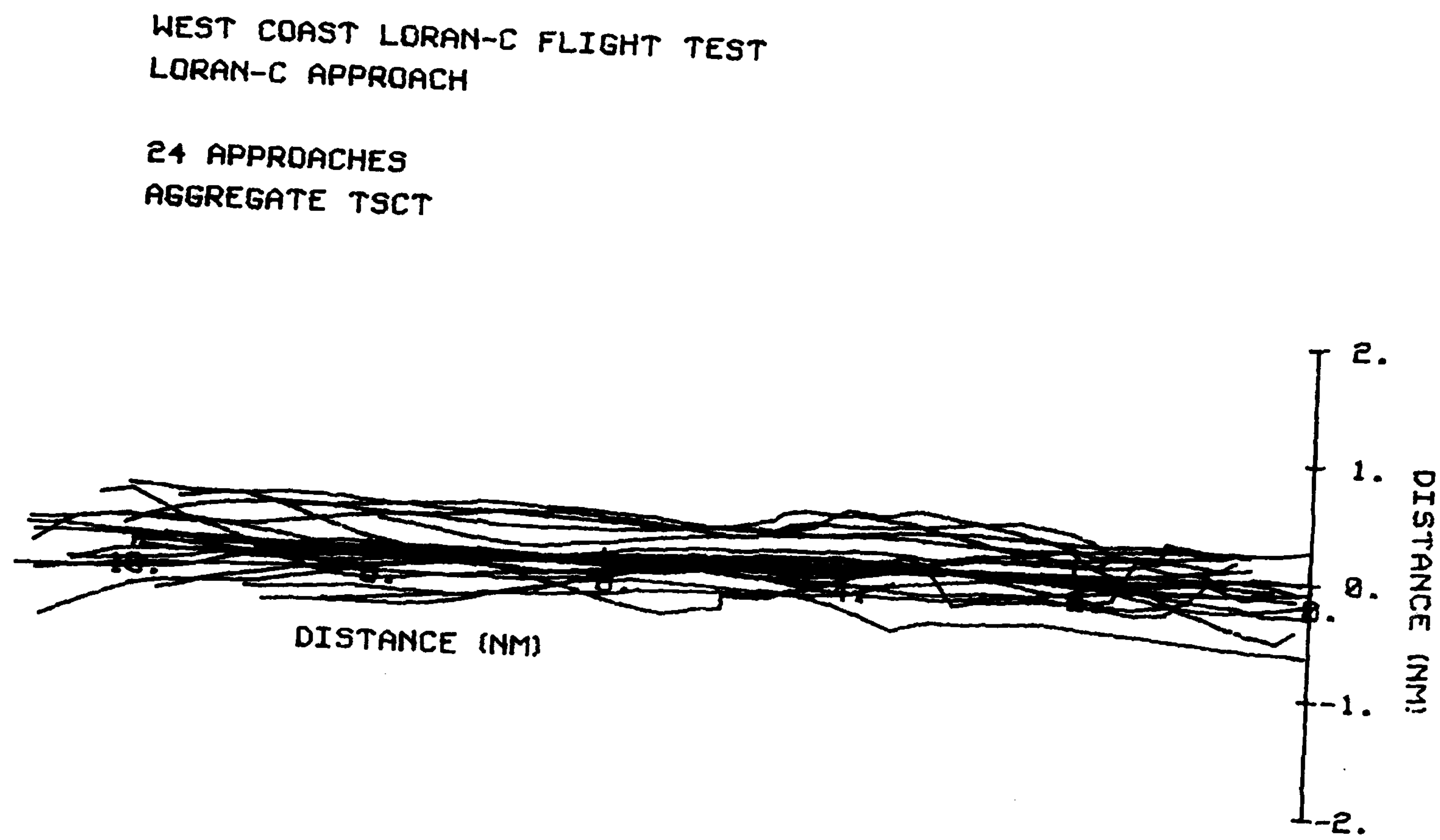

Figure 6.9 Total System Cross Track Error Aggregate Plot

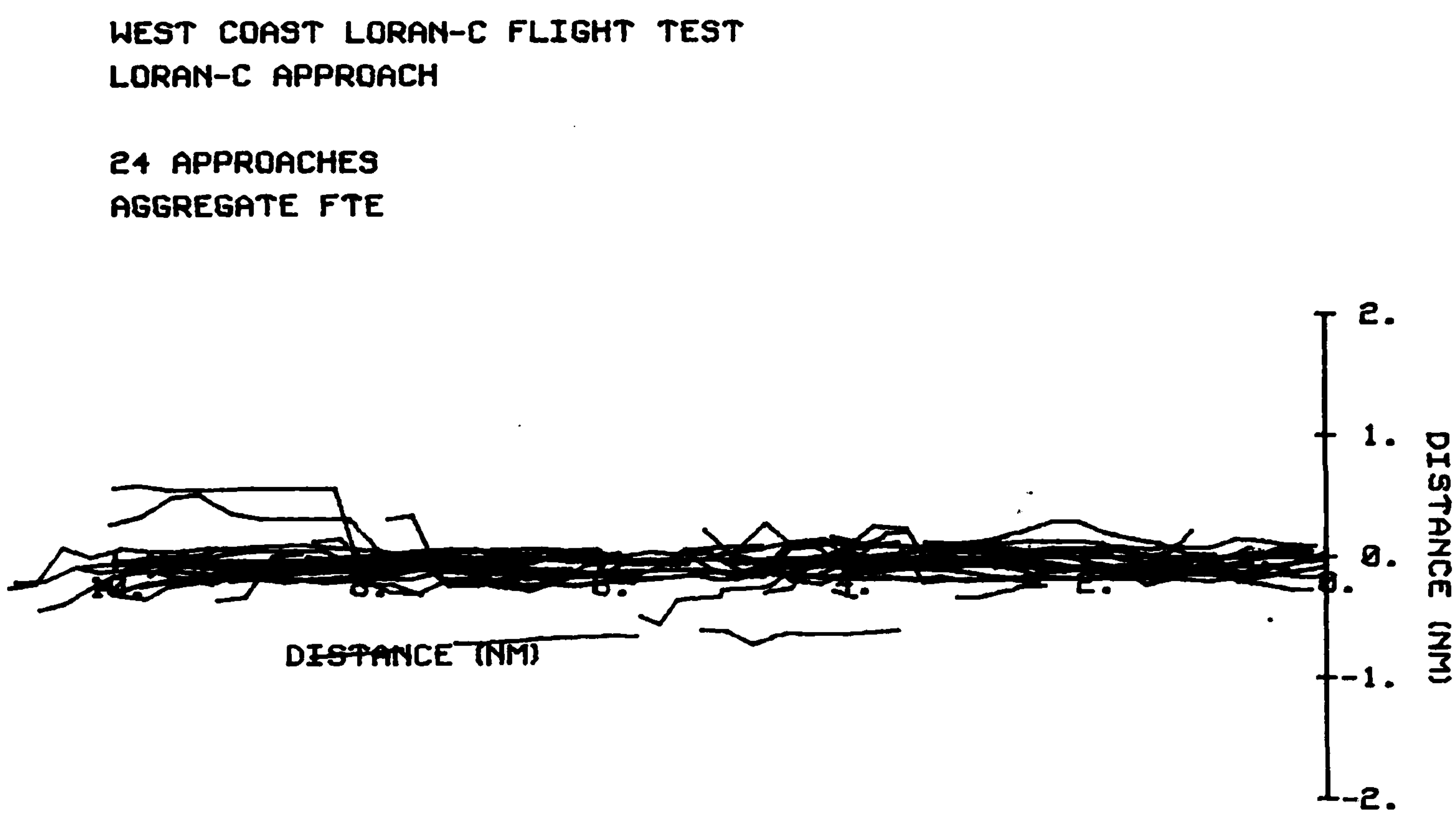

Figure 6.10 Flight Technical Error Aggregate Plot

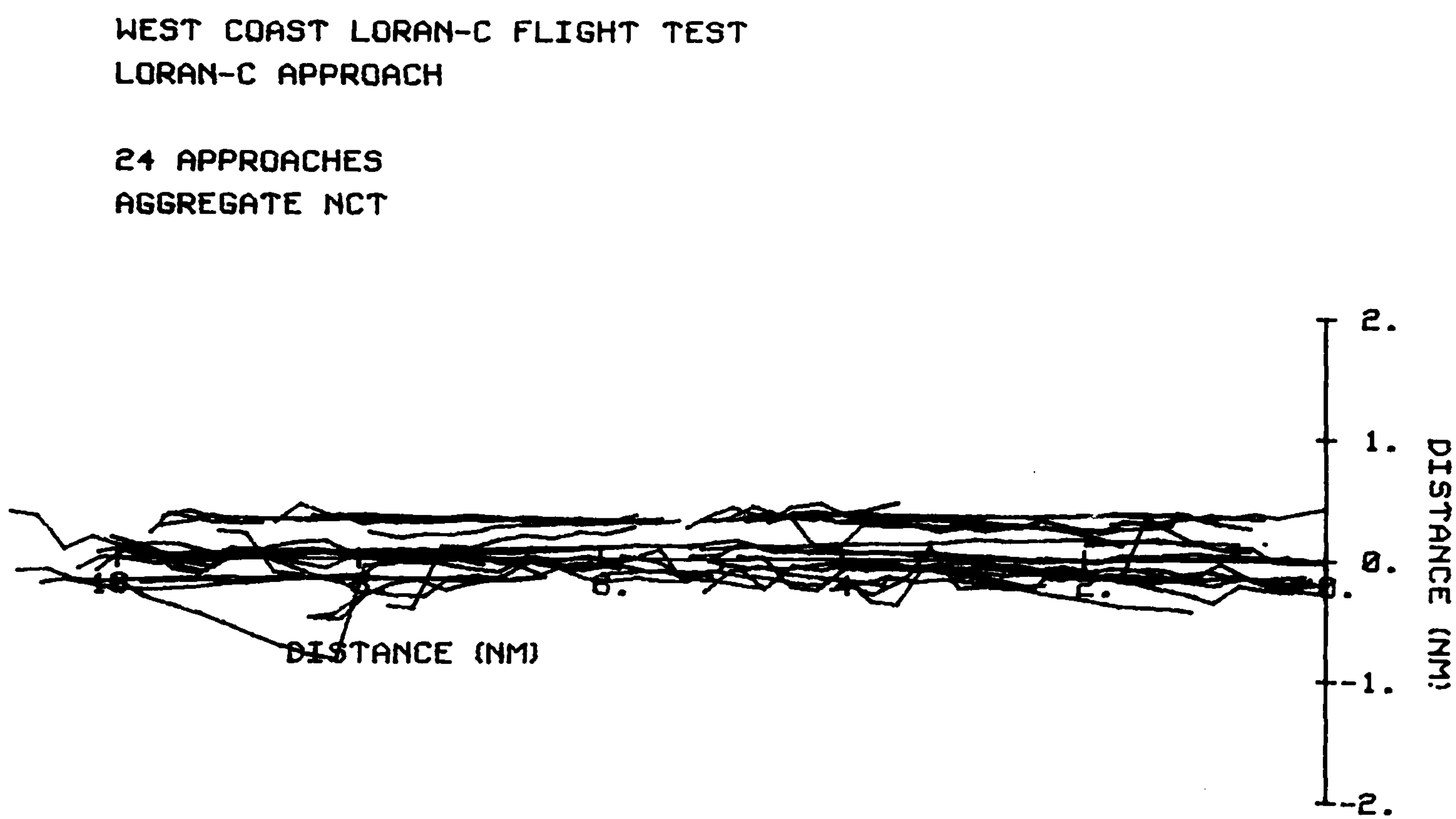

Figure 6.11 Navigation Cross Track Error Aggregate Plot

In Tables 6.8 and 6.9 the statistical summaries of the test results are presented. The first table contains the so-called unfiltered data, while the second is filtered. The difference between the two is related to the characteristic of the TDL-711 to interrupt the output data stream periodically. This interruption, or data freeze, can last from several seconds to approximately one minute. The difference is that in the filtered data, each occurrence of a Loran-C data output freeze or lockout has been detected, and all but the very first data sample during the lockout period has been discarded. When a data lockout occurs, the apparent navigation errors tend to grow with time since the aircraft is in motion. Therefore, while the unfiltered data accurately represents the performance of the specific navigator under test, the filtered data is more nearly representative of Loran-C performance in general.

Tables 6.8 and 6.9 show another factor which deserves explanation. For any given approach location, the numbers of data points shown for Northing and Easting errors may be different from the numbers of points shown for the track-related errors. This results from the fact that valid position data is produced by the navigator during all flight phases, while valid track guidance is only produced while conducting the approach phase of these tests. Hence, there are fewer track-related error data points.

Examination of Table 6.9, Filtered Error Statistics, shows several Loran-C characteristics which will be discussed in detail. First of all, the Loran-C grid bias shift which can result from selecting two different triads in a given locality is exemplified in several cases. At Stead the shift in bias:

STEAD	N	E
FMG	-.31	.25
FMS	.86	-.01

is in excess of one mile northerly, and is quite small easterly. A similar shift occurs at South Lake Tahoe:

Table 6.8 Unfiltered Error Statistics West Coast Loran-C Flight Test

Location/ Triad	# of Appr's	Pts	Northing		Easting		Pts	FTE		TSCT		NCT		NAT	
			$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Reno/FMS	3	80	.82	.23	-.09	.05	56	.11	.08	.01	.07	-.11	.05	.69	.23
Stead/FMG	1	22	-.31	.30	.25	.39	17	.13	.35	.35	.18	.21	.23	.23	.13
Stead/FMS	1	22	.86	.09	-.01	.17	14	.09	.13	-.76	.08	-.85	.09	-.17	.18
Klamath/FMG	6	270	-.05	.13	.16	.10	228	-.03	.17	.05	.15	.08	.14	.08	.14
Tahoe/FMS*	6	225	.47	.12	-.15	.07	200	.09	.21	-.23	.20	-.33	.06	.39	.13
Tahoe/FMG*	3	92	-.45	.20	.13	.16	86	.04	.14	.21	.12	.17	.08	-.48	.11
Grand Junction/ FGS	1	41	-.40	.16	-.27	.28	36	.13	.15	-.07	.10	-.21	.20	.00	.08
Test Total	21	752	.15	.44	.00	.21	637	.05	.19	-.04	.25	-.09	.26	.15	.35

*Includes Approaches on 7 Jul 79 and 26 Jul 79.

Table 6.9 Filtered Error Statistics West Coast Loran-C Flight Test

Location/ Triad	# of Appr's	Pts	Northing		Easting		Pts	FTE		TSCT		NCT		NAT	
			$\overline{x}$	σ	$\overline{x}$	σ		$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
Reno/FMS	3	56	.80	.16	-.11	.05	56	.11	.08	.01	.07	-.11	.05	.75	.16
Stead/FMG	1	16	-.31	.11	.25	.13	16	.14	.35	.34	.19	.20	.22	.22	.13
Stead/FMS	1	12	.86	.10	-.01	.18	12	.09	.14	-.76	.10	-.85	.10	-.18	.18
Klamath/FMG	6	249	-.02	.06	.15	.10	209	-.02	.16	.05	.15	.07	.12	.04	.06
Tahoe/FMS*	6	225	.47	.12	-.15	.07	200	.09	.21	-.23	.20	-.33	.06	.39	.13
Tahoe/FMG*	3	90	-.47	.12	.15	.12	86	.04	.14	.21	.12	.17	.08	-.48	.11
Grand Junction/ FGS	1	41	-.36	.16	-.33	.28	36	.13	.15	-.07	.10	-.21	.20	.00	.08
Test Total	21	689	.14	.41	.00	.20	615	.05	.18	-.04	.25	-.10	.25	.14	.36

*Includes Approaches on 7 Jul 79 and 26 Jul 79.

TAHOE	$\bar{N}$	$\bar{E}$
FMG	-.47	.15
FMS	.47	-.15

A very large bias shift was observed at Grand Junction. Biases using FGS are reasonably small, while those using FMG were so large (several miles) that only data in the area calibrated mode was taken. Grand Junction is in the baseline extension area of the Fallon-Middletown pair, and so large errors were anticipated. A similar situation was expected with respect to the Fallon-Searchlight pair at Klamath Falls, However, the navigator was unable to converge on a solution for the FMS triad at that location. It was determined during the data reduction phase that, due to the errors which existed in the measured TD values, a solution was indeed impossible. This situation was discussed in Section 6.1.

The standard deviation data presented in Table 6.9 is quite illuminating. Disregarding the Stead flights (which were not conducted as full approach procedures), the standard deviations of the northing and easting errors range from .05 to .28 nm at individual sites. The aggregate (Test Total) values are somewhat larger, σ_N = .41 and σ_E = .20. This results from the fact that the biases at the several sites, and due to use of different triads, are different and show up in the σ value when aggregated (aggregate means are small by comparison).

The standard deviations of the track-related errors are also of significant interest. The aggregate FTE values (mean = .05, σ = .18) are approximately equivalent to the FTE statistics for the individual airports, since the Loran-C biases do not appear in the FTE term. Alternatively, the aggregate sigma values for the remaining terms (σ_{TSCT} = .25, σ_{NCT} = .25, σ_{NAT} = .36) are larger than the sigma values for individual airports since the Loran-C biases appear in these error terms. By the same token the aggregate bias terms are smaller than some of those found at individual airports. An interesting side issue concerns the relative magnitudes of along track and cross track navigation error (σ_{NCT} = .25, σ_{NAT} = .36). The fact that one value is

considerably larger than the other is due primarily to circumstance: the Loran-C biases experienced during the tests were primarily oriented in the along track direction with respect to the runways selected.

It is appropriate to comment further on the aggregate data shown in Tables 6.8 and 6.9. Arithmetically, the aggregation process consists of the following: Given the values for mean, standard deviation and number of points measured for several approach locations, "grand total" values for mean, standard deviation and total points are calculated. This is done by converting the given data into raw Σx, Σx^2 and N data, computing grand Σx, Σx^2 and N valves, and computing the mean and S.D. from those values. This is equivalent to computing the mean and S.D. given all of the raw error values measured in the tests. Although this is an arithmetically valid computational step, the statistical interpretation of the resulting data is open to question. Since the data collected was recorded under widely varying conditions of triad and GDOP, the resulting aggregates are not necessarily representative of Loran-C performance at any given location. This problem is of importance in the interpretation of approach airspace requirements, discussed later.

In Tables 6.10 and 6.11 the equivalent unfiltered and filtered statistics for the area calibrated flights were presented. In the Tahoe area calibrated tests the calibration procedure essentially eliminated the Loran-C biases (FMG Triad):

TAHOE	$\bar{N}$	$\bar{E}$
No Area Cal.	-.47	.15
Area Calibrated	-.19	.00

The sigma values are also lower although these probably resulted from the lower FTE values rather than the area calibration technique.

The other area calibration tests were run at Grand Junction. As mentioned above, the biases were on the order of several miles without area calibration. Even with area calibration the residual bias errors are significant (on the order of these experienced without area calibration using triads offering good geometry):

Table 6.10 Unfiltered Error Statistics West Coast Loran-C Flight Test with Area Calibration

Location/ Triad	# of Appr's	Pts	Northing		Easting		Pts	FTE		TSCT		NCT		NAT	
			$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Tahoe/FMG	3	155	-.17	.11	.00	.05	122	.08	.06	.03	.06	-.05	.04	-.20	.11

Location/ Triad	# of Appr's	Pts	Northing		Easting		Pts	FTE		TSCT		NCT		NAT	
			$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Grand Junction/ FMG	2	63	.31	.11	-.56	.16	53	.09	.14	.25	.16	.16	.15	.63	.15

Table 6.11 Filtered Error Statistics West Coast Loran-C Flight Test With Area Calibration

Location/ Triad	# of Appr's	Pts	Northing		Easting		Pts	FTE		TSCT		NCT		NAT	
			$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Tahoe/FMG	3	143	-.19	.07	.00	.05	110	.08	.06	.03	.06	-.05	.04	-.22	.08

Location/ Triad	# of Appr's	Pts	Northing		Easting		Pts	FTE		TSCT		NCT		NAT	
			$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Grand Junction/ FMG	2	58	.29	.10	-.54	.14	48	.09	.15	.25	.16	.16	.16	.60	.13

GRAND JUNCTION	$\bar{N}$	$\bar{E}$
FGS - No Area Cal.	-.36	-.33
FMG - Area Calibrated	.29	-.54

The residual biases were detected during the area calibration procedure itself. At that time, even though the exact calibration point lat/lon coordinates were input to the navigator, when it responded and displayed present position, the displayed value was in error (the procedure was repeated several times). This problem is undoubtedly related to the extremely poor Loran-C LOP geometry which exists at that location.

With reference to the filtered (Table 6.9) versus unfiltered (Table 6.8) data presented earlier, two special plots are presented here in order to demonstrate the randomly occurring pattern of data output lockouts which characterized the TDL-711 unit under test. In Figure 6.12 and 6.13 appear plots of six parameters (the sensed time differences, the computed latitude and longitude values, along track distance and cross track deviation). These plots were originally designed to demonstrate the immediate correlation of changes in lat/lon values to fluctuations in measured time differences. However, besides doing that they vividly illustrate data lockouts, which are indicated by breaks in the graph lines. (An additional break occurs in line 5, along track distance, at the waypoint changeover point). In the first Figure, for South Lake Tahoe, five data lockouts occurred during some 290 seconds of data. The second figure, for Klamath Falls, three lockouts occurred during 250 seconds of data. Note that the lockouts occur with varying durations.

Returning to the non-area calibrated, filtered data (Table 6.9), a careful comparison of the northing/easting errors with the navigation along/cross track (NAT, NCT) errors was made. Both of these error measures are manifestations of Loran-C positioning error, except that the error is expressed in different coordinate systems (North and East as opposed to track coordinates). Since they are expressions of the same error source, they should (when expressed as a vector magnitude) be of the same magnitude. (This will not be rigorously true since N,

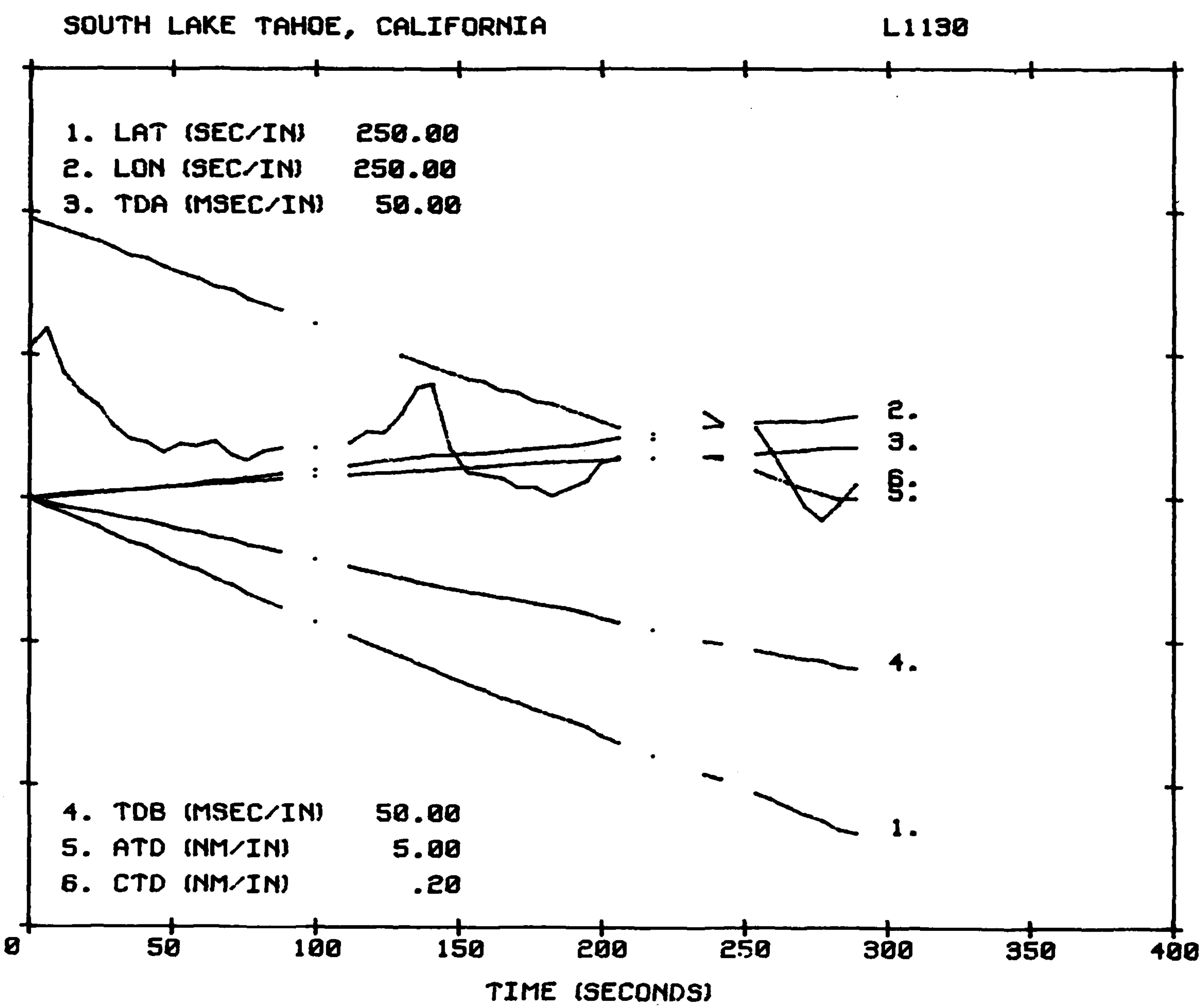

Figure 6.12 Six-Parameter Plot

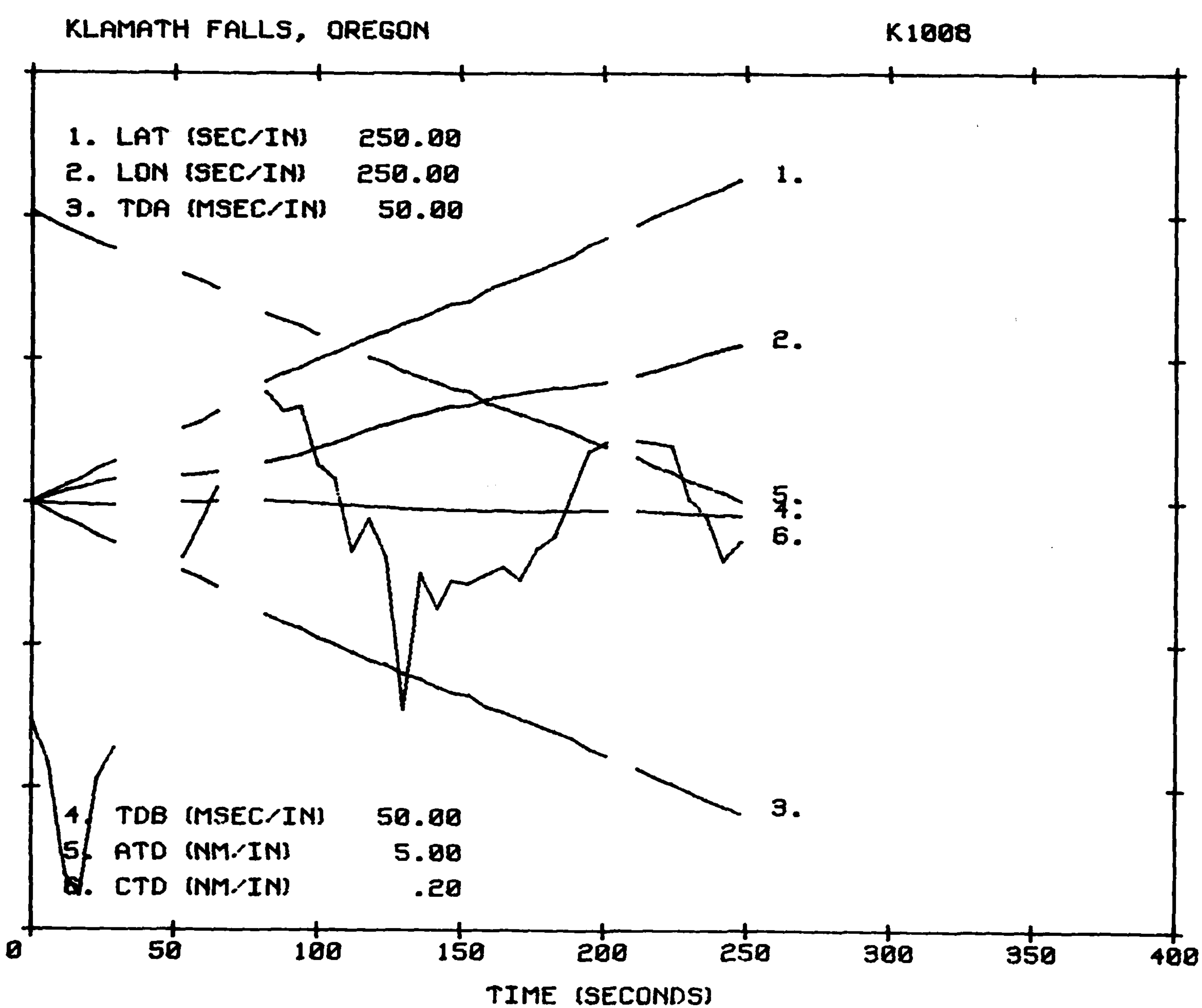

Figure 6.13 Six-Parameter Plot

E errors were calculated at a few points where AT, CT values are not valid). However, this equivalence did not necessarily occur:

GRAND JUNCTION (FGS)

$\bar{N}$	$\bar{E}$	Magnitude
-.36	-.33	.49
NCT	NAT	Magnitude
-.21	.00	.21

KLAMATH (FMG)

$\bar{N}$	$\bar{E}$	Magnitude
-.02	.15	.15
NCT	NAT	Magnitude
.07	.04	.08

Furthermore, in some instances where the runway orientation was primarily N/S or E/W, the Northing/Along Track and Easting/Cross Track values (or vice versa) should be equivalent. However:

STEAD (FMS)

Runway Azimuth: ~270°
Easting Error: .03
Along Track Error: -.18

Due to these results, the coordinate conversion capabilities of the navigator were analyzed in detail as discussed in Section 6.1. This was done in two steps: First, the raw time difference data recorded during the tests was converted to latitude and longitude utilizing a spheroidal earth model and standard USCG propagation assumptions. The resulting values were compared to the navigator Lat/Lon output to yield an error value expressed in feet. The results of these analyses (in statistical terms) is presented in Table 6.5, which appears in Section 6.1. In summary:

TD to Lat/Lon Coordinate Conversion Errors (Feet)

	Mean	S.D.
Lat Error	71'	86'
Lon Error	-32'	29'

It is apparent from these statistics that the TDL-711 computes latitude and longitude quite accurately from the measured TD data. For purposes of the remaining analysis, these errors were considered to be negligible.

The second analysis concerned conversion of the latitude/longitude information to along and cross track coordinates. These results are presented in Table 6.12. In summary:

Lat/Lon To Along/Cross Track Coordinate Conversion Errors (nm)

	Mean	S.D.
Along Track Error	-.04	.04
Cross Track Error	.04	.15

Table 6.12 Along/Cross Track Coordinate Conversion Errors (nm)

Location/Triad	N Points	Cross Track		Along Track	
		Mean	σ	Mean	σ
RENO/FMS	56	.00	.01	-.05	.04
STEAD/FMG	16	-.07	.17	-.06	.03
STEAD/FMS	12	.00	.09	-.06	.03
KAMATH/FMG	209	.19	.05	-.04	.04
TAHOE/FMS	200	-.08	.03	-.05	.03
TAHOE/FMG	86	-.07	.04	-.05	.03
GJT/FGS	36	.27	.15	.00	.04
TOTAL	615	.04	.15	-.04	.04

In contrast to the lat/lon conversion process, the track - coordinate conversion process is quite unpredictable and inaccurate. In a few cases (particularly Klamath Falls (0.19 nm) and Grand Junction (0.27 nm) in the cross track direction) the errors were of the same magnitude as the raw Loran-C errors themselves. The errors seemed to be rather constant at a given airport and insensitve to triad in use or area calibration mode. An exception to this case is the Stead case, where the coordinate conversion error in the cross track direction changed throughout the approaches. One of these approaches is illustrated in Figure 6.14. This plot was constructed directly from the navigator RDU data stream using manual techniques. The use of the RAPPS/Loran-C error analysis computer program and the coordinate conversion error analysis program was therefore avoided totally, eliminating those analysis tools as possible sources of the errors detected.

Since a complete survey of coordinate conversion errors was conducted, it is possible to recreate Table 6.9 with the error components broken down into sensor error and computer error terms; e.g.

$$NCT = SCT + CCT$$

$$NAT = SAT + CAT$$

Where SCT, SAT represent the Loran-C sensor cross/along track error quantities, and CCT, CAT represent the navigation computer coordinate conversion error quantities. The recreated figures appear as Table 6.13 (filtered data only). In this table the magnitudes of the SCT/SAT components are not equal to the magnitudes of the Northing/Easting components.

In Section 5.4 a summary of the requirements of FAA Advisory Circular AC 90-45A for non-VOR/DME referenced area navigation systems is presented. The results of this test program (from Table 6.9) are compared to the 90-45A approach criteria in Table 6.14 (means were neglected since in the data aggregation process they result as contributions to the standard deviations). The overall cross track performance in the Loran-C tests of 0.50 nm (2σ) is within the expressed requirement of 0.60 nm. Also, the FTE values measured (0.37) are

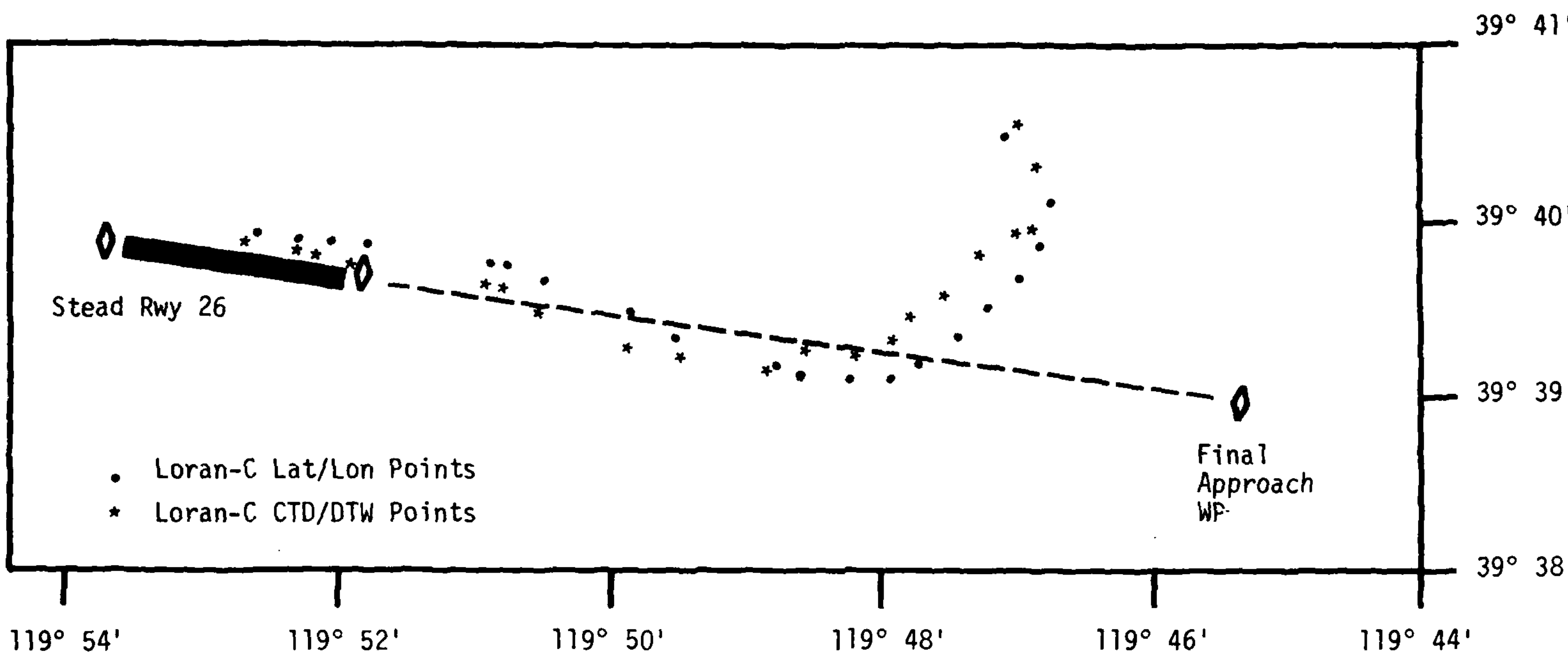

Figure 6.14 Plot of Loran-C Lat/Lon Position and CTD/DTW Position During Approach to Reno/Stead

Table 6.13 Filtered Error Statistics with Sensor and Computer Errors Isolated

Location/ Triad	# of Appr's	Pts	Northing		Easting		Pts	FTE		TSCT		SCT		CCT		SAT		CAT	
			$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Reno/FMS	3	56	.80	.16	-.11	.05	56	.11	.08	.01	.07	-.11	.04	.00	.01	.80	.16	-.05	.04
Stead/FMG	1	16	-.31	.11	.25	.13	16	.14	.35	.34	.19	.27	.14	-.07	.17	.28	.13	-.06	.03
Stead/FMS	1	12	.86	.10	-.01	.18	12	.09	.14	-.76	.10	-.85	.05	.00	.09	-.12	.18	-.06	.03
Klamath/FMG	6	249	-.02	.06	.15	.10	209	-.02	.16	.05	.15	-.12	.11	.19	.05	.08	.05	-.04	.04
Tahoe/FMS*	6	225	.47	.12	-.15	.07	200	.09	.21	-.23	.20	-.24	.05	-.08	.03	.43	.13	-.05	.03
Tahoe/FMG*	3	90	-.47	.12	.15	.12	86	.04	.14	.21	.12	.25	.07	-.07	.04	-.43	.11	-.05	.03
Grand Junction/ FGS	1	41	-.36	.16	-.33	.28	36	.13	.15	-.07	.10	-.48	.13	.27	.15	.00	.07	.00	.04
Test Total	21	689	.14	.41	.00	.20	615	.05	.18	-.04	.25	-.13	.23	.04	.15	.18	.36	-.04	.04

*Includes Approaches on 7 Jul 79 and 26 Jul 79.

Table 6.14 Comparison of Test Results With AC 90-45A Criteria

	AC 90-45A Approach Criteria (2σ)		Loran-C Test Results (2σ)	
	Cross Track	Along Track	Cross Track	Along Track
Airspace(TSCT)	0.6	0.3	0.50	0.71
FTE	0.5	---	0.37	---
Loran-C	0.3	0.3	0.49	0.71

better than required (0.5). However, the measured cross track navigation error of 0.49 exceeds the 0.3 requirement. Likewise, the 0.71 nm (2σ) along track navigation error value exceeds the stated requirement for 0.3 nm along track performance. As stated in detail earlier, the large along and cross track sigma values result mainly from the fact that the biases experienced at each location, when arithmetically aggregated, end up enlarging the sigma results.

It can be concluded from these results that the Root-Sum-Square error combination technique does not yield results consistent with the measured data:

Measured NCT	Measured FTE	Computed RSS-CT	Measured TSCT
0.49	0.37	$\sqrt{.49^2 + .37^2} = 0.61$	0.50

Interestingly enough, the RSS-CT airspace value computed by this method meets the AC 90-45A cross track requirement (0.6 nm). Alternatively, if the specificed FTE value is used:

Measured NCT	Specified FTE	Computed RSS-CT	Measured TSCT
0.49	0.50	$\sqrt{.49^2 + .50^2} = 0.70$	0.50

Then the computed value is even higher, outside of the AC 90-45A criteria.

As an alternative approach to the airspace and procedure design problem, there are several methods by which the biases which were measured during these tests may be eliminated for purposes of conducting instrument approaches. They include:

1) Using measured TDs for waypoint coordinates
2) Using measured lat/lons for waypoint coordinates
3) Implementing a differential Loran-C concept
4) Using an improved propagation model

In order to evaluate these possibilities, the summary statistics of Table 6.14 have been recalculated with the biases eliminated. These results are summarized in Table 6.15. Notice in that table that FTE changes only very slightly, but that all other errors drop dramatically and are well within AC 90-45A criteria. Even if the measured NCT value (0.21) is RSS combined with the 0.5 nm FTE specification, the result is 0.54, which is less than the 0.6 mile criteria. The along track value (0.23) is well within the 0.3 nm specification. Notice also that the Loran-C along track and cross track values are now approximately equivalent.

Table 6.15 Comparison of Bias-Corrected Test Results with AC 90-45A Criteria

	AC 90-45A Approach Criteria (2σ)		Bias-Corrected Test Results (2σ)	
	Cross Track	Along Track	Cross Track	Along Track
Airspace (TSCT)	0.6	0.3	0.31	0.22
FTE	0.5	---	0.35	---
Loran-C	0.3	0.3	0.21	0.23

7.0 CONCLUSIONS

Based on the experience gained from operating the TDL-711 Loran-C navigator during the test flights, and evaluating the data which was recorded during those tests, the following conclusions have been developed. An effort has been made to isolate the performance characteristics of Loran-C from characteristics of the specific navigator under test. Considering the performance characteristics and problems encountered, an assessment of the applicability of Loran-C as an non-precision approach aid is also presented.

7.1 LORAN-C WEST COAST CHAIN PERFORMANCE

- Based on a review of Loran-C time difference data and signal-to-noise ratio values recorded during the test approaches which were conducted, Loran-C chain reliability was found to be very good. There were but two occurrences of a situation where a loss of TD tracking occurred in-flight. Those losses (which were momentary) were confirmed to have been caused by temporary station outages.
- The West Coast Loran-C chain appears to be stable and well controlled. Navigation data was stable with respect to time (similar results were obtained at South Lake Tahoe on July 7 and July 26).
- Errors which were measured were consistent (biases) as opposed to being random in nature. Upon examination, it was found that time difference errors measured could be related to consistent propagation delay factors, such as would be expected to result from the fact that the radio waves are propagating over land (low conductivity) rather than sea water (high conductivity).
- Time difference bias errors would be reduced considerably if a land conductivity value were included in the propagation model in the navigator. However, that approach oversimplifies the propagation modeling problem, in that errors would probably be introduced when overwater propagation paths are involved.

- While basically stable at a site, the Loran-C time differences did exhibit variabilities during the approaches. Local grid warpage was evident to a minor extent. Also, jitter in some of the measurements was evident. Conclusive evidence identifying causes for these effects could not be found.

7.2 PERFORMANCE OF THE TDL-711

- In general the TDL-711 is reasonably easy to operate and does not impose an undue burden on the flight crew during an approach since the waypoints are programmed well ahead of the actual approach. Like many RNAV systems, last minutes changes in active runway or routings could create a workload problem.

- In general, the guidance information was stable and repeatable, which would inspire a degree of confidence in the flight crew. However, the unit had a disturbing habit of unexpectedly losing track of its internal latitude/longitude solution, which would cause it to revert to a search mode for approximately one-half minute or longer. While the guidance data was properly flagged, this is quite disconcerting to the flight crew. It is assumed that this problem can be tied to the system software, and may have already been corrected in subsequent versions of the operating software.

- The navigator has been shown through analysis to very accurately calculate latitude/longitude from the measured time difference values, compared to a standard propagation model utilizing no secondary delay correction factors. There were found, however, to be errors in the calculation of cross track deviation and distance to waypoint. These errors were found to range from zero up to one-quarter mile, and so none were found to be so large as to exceed the system accuracy requirement for RNAV approach capability contained in AC90-45A. However, in combination with the

errors in the Loran-C system itself, these coordinate conversion errors make meeting the AC90-45A criteria even more difficult (see Section 7.3, below) than would otherwise be the case.

- The TDL-711 exhibited the capability to initially acquire the chain and converge on a solution within approximately two minutes or less. For most operations this is not an unreasonable length of time. Also, waypoints can be entered during the interim. The time required to lock-on could be considered an operational problem since it occurs whenever a different area is selected; however, an area (triad) change would probably not be a routine procedure during terminal operations.

- The results presented in this report should not be interpreted as being absolutely representative of Loran-C performance in general, Loran-C navigators in general, or even the TDL-711 in general. The tests were confined to one Loran-C chain specifically. The TDL-711 is representative of one manufacturer's equipment only, and even within that product line improvements to operating software reportedly have been made since the tests were conducted.

7.3 LORAN-C AS AN APPROACH AID

In this section an attempt is made to consider only those problems and factors which appear to be characteristic of Loran-C in general or Loran-C navigators in general, given the limitations of current technology.

- Based on the data collected in this study, it appears that the sensor accuracy requirements of AC90-45A would not be met unless hardware, software or procedural modifications are made. Since there are operational techniques for minimizing the errors which are manifested as locally-consistent biases, and since there are ways to improve the propagation models within navigators, this accuracy problem should be resolvable.

- The approach procedures conducted were quite easily performed by the flight crew. The Loran-C signals themselves appeared to be quite consistent and reliable. Disregarding the idiosyncrasies of the particular unit under test, the approaches can be performed with ease.

- Concerning data entry errors, Loran-C exhibits the same basic drawback as all area coverage radio approach aids (such as OMEGA, VOR/DME RNAV, GPS, etc.): Errors in specifying waypoint coordinates or station (in this case triad) selection can be made and could be catastrophic. There is no built-in confidence-builder/cross-check such as is the case with other non-precision approach systems (station passage for VOR and NDB approaches; marker beacon passage for LOC approaches). It would be highly advantageous if some form of independent cross-check were available (VOR radial, DME range, NDB passage, radar fix, ground mapping radar, radio altimeter etc.).

- Notwithstanding the above reservations, Loran-C holds the promise to be a widely applicable enroute navigation and approach aid, particularly at remote airports which could not support an instrument landing system.

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APPENDIX A

LORAN-C APPROACH TEST DATA PLOTS

APPENDIX A

LORAN-C APPROACH TEST DATA PLOTS

Plots of the test approach procedures are included in this appendix as follows:

1) Klamath Falls, Oregon

   6 Plots of TSCT and FTE
   1 FTE Aggregate Plot
   1 NCT Aggregate Plot
   1 TSCT Aggregate Plot

2) South Lake Tahoe, California

   12 Plots of TSCT and FTE
   1 FTE Aggregate Plot
   1 NCT Aggregate Plot
   1 TSCT Aggregate Plot

3) Grand Junction, Colorado

   3 Plots of TSCT and FTE
   1 FTE Aggregate Plot
   1 NCT Aggregate Plot
   1 TSCT Aggregate Plot

4) Reno International

   3 Plots of TSCT and FTE
   1 FTE Aggregate Plot
   1 NCT Aggregate Plot
   1 TSCT Aggregate Plot

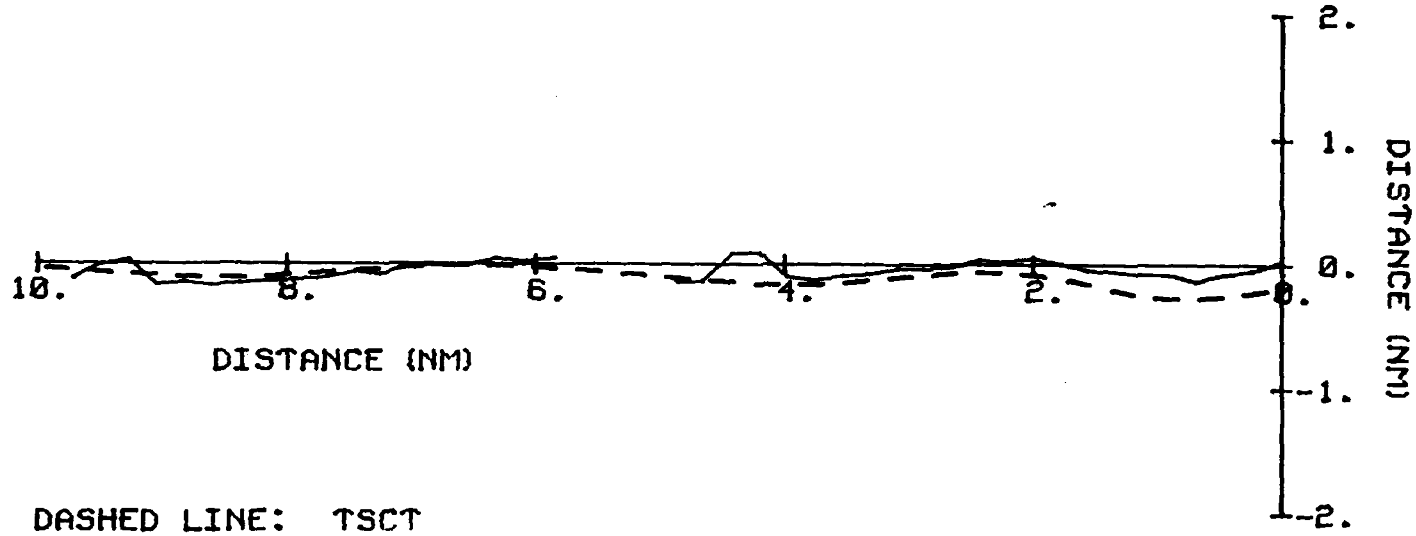
5) Reno/Stead

   2 Plots of TSCT and FTE
   1 FTE Aggregate Plot
   1 NCT Aggregate Plot
   1 TSCT Aggregate Plot

KLAMATH FALLS, OREGON
LORAN-C APPROACH RUNWAY 32

KL083640
24 JUL 79

TRIAD: F-M-G
AREA CAL: NO
PILOT: S (HOODED)



DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.1 Klamath Falls, Oregon Loran-C Approach Runway 32

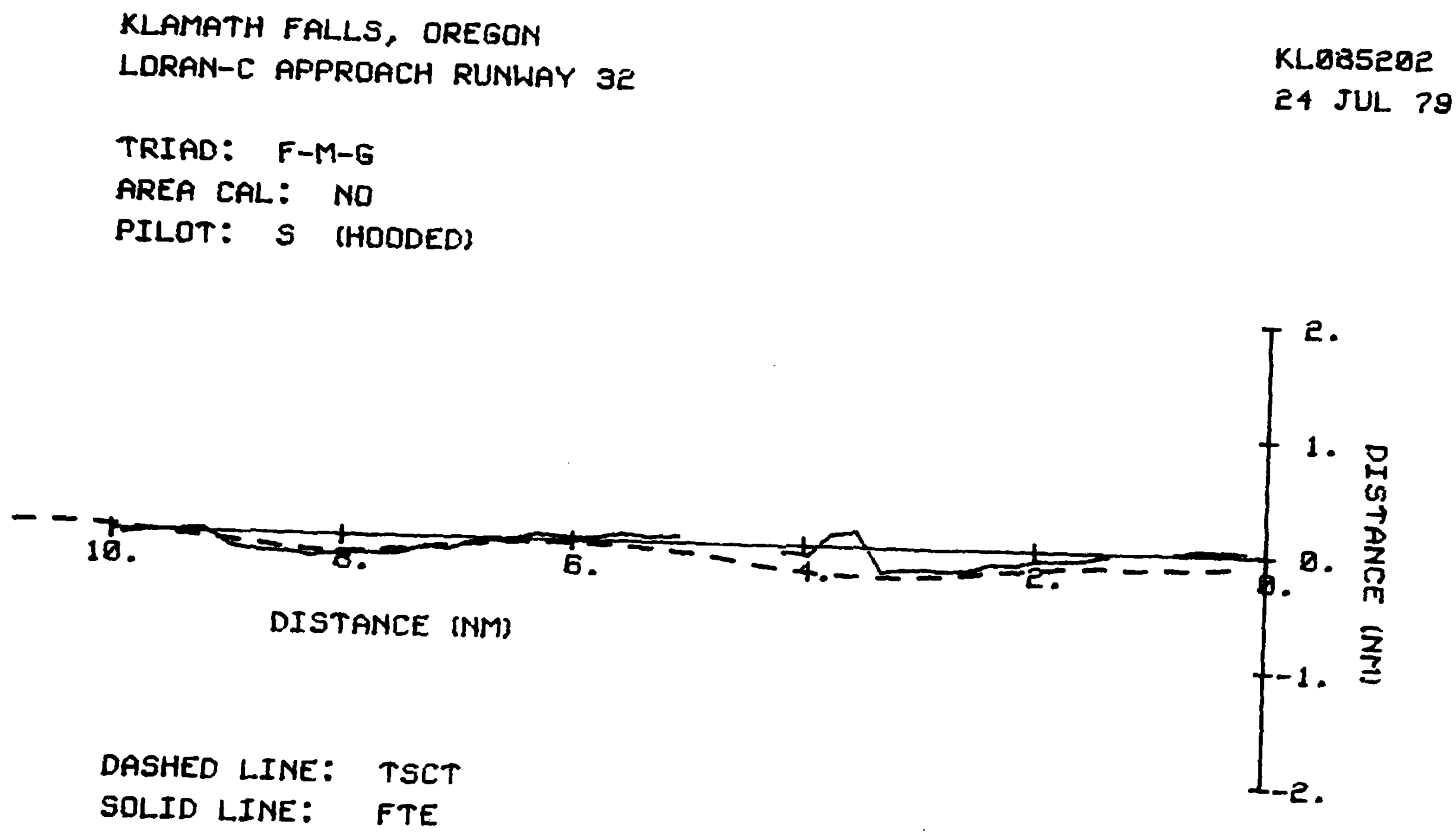
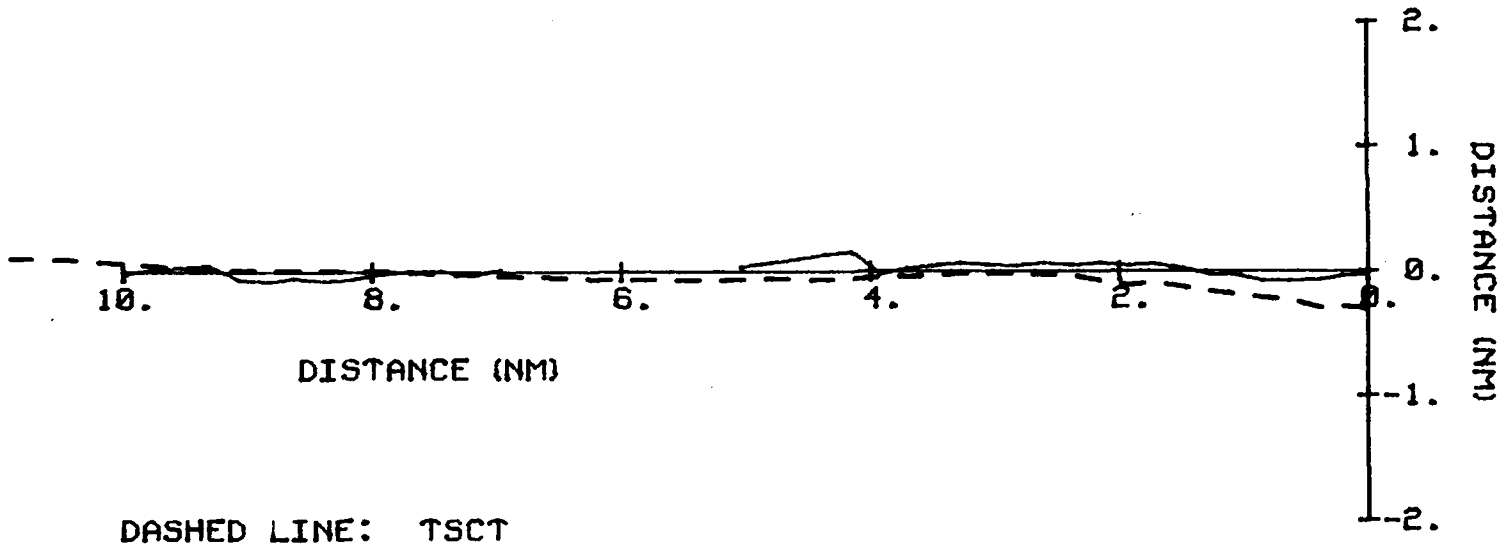


Figure A.2 Klamath Falls, Oregon Loran-C Approach Runway 32

KLAMATH FALLS, OREGON
LORAN-C APPROACH RUNWAY 32

KL090712
24 JUL 79

TRIAD: F-M-G
AREA CAL: NO
PILOT: S (HOODED)



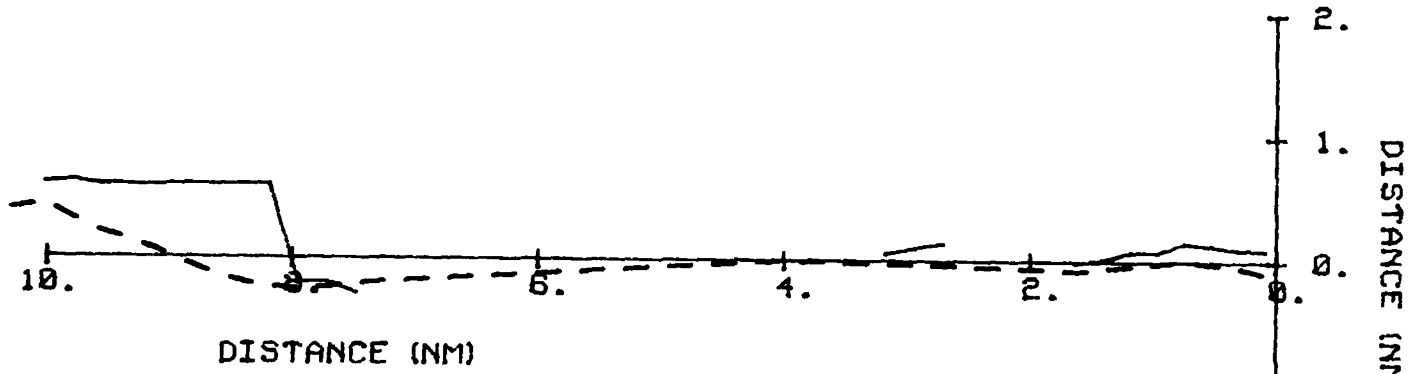
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.3 Klamath Falls, Oregon Loran-C Approach Runway 32

KLAMATH FALLS, OREGON
LORAN-C APPROACH RUNWAY 32

KL093524
24 JUL 79

TRIAD: F-M-G
AREA CAL: NO
PILOT: R (HOODED)



DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.4 Klamath Falls, Oregon Loran-C Approach Runway 32

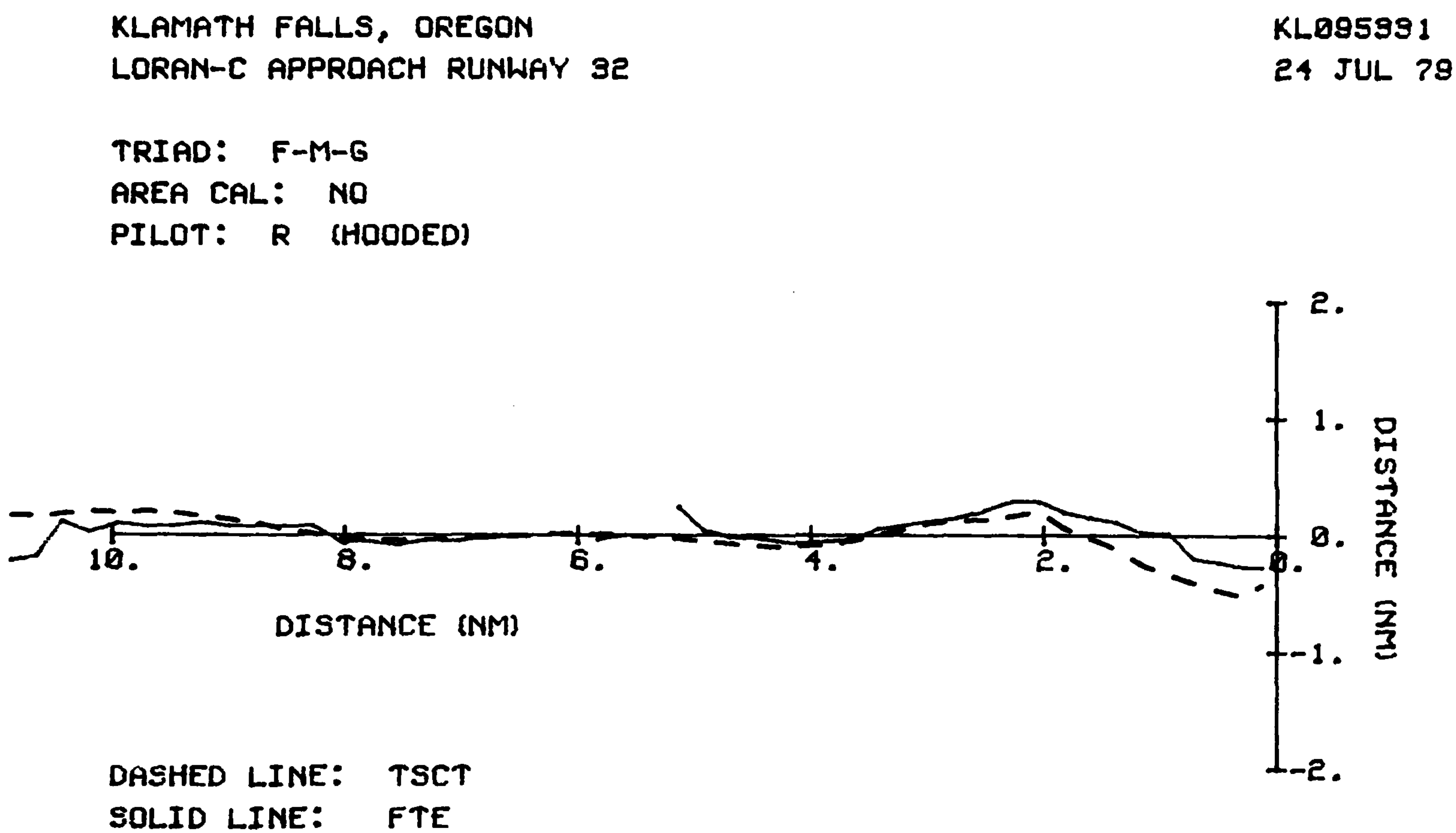


Figure A.5 Klamath Falls, Oregon Loran-C Approach Runway 32

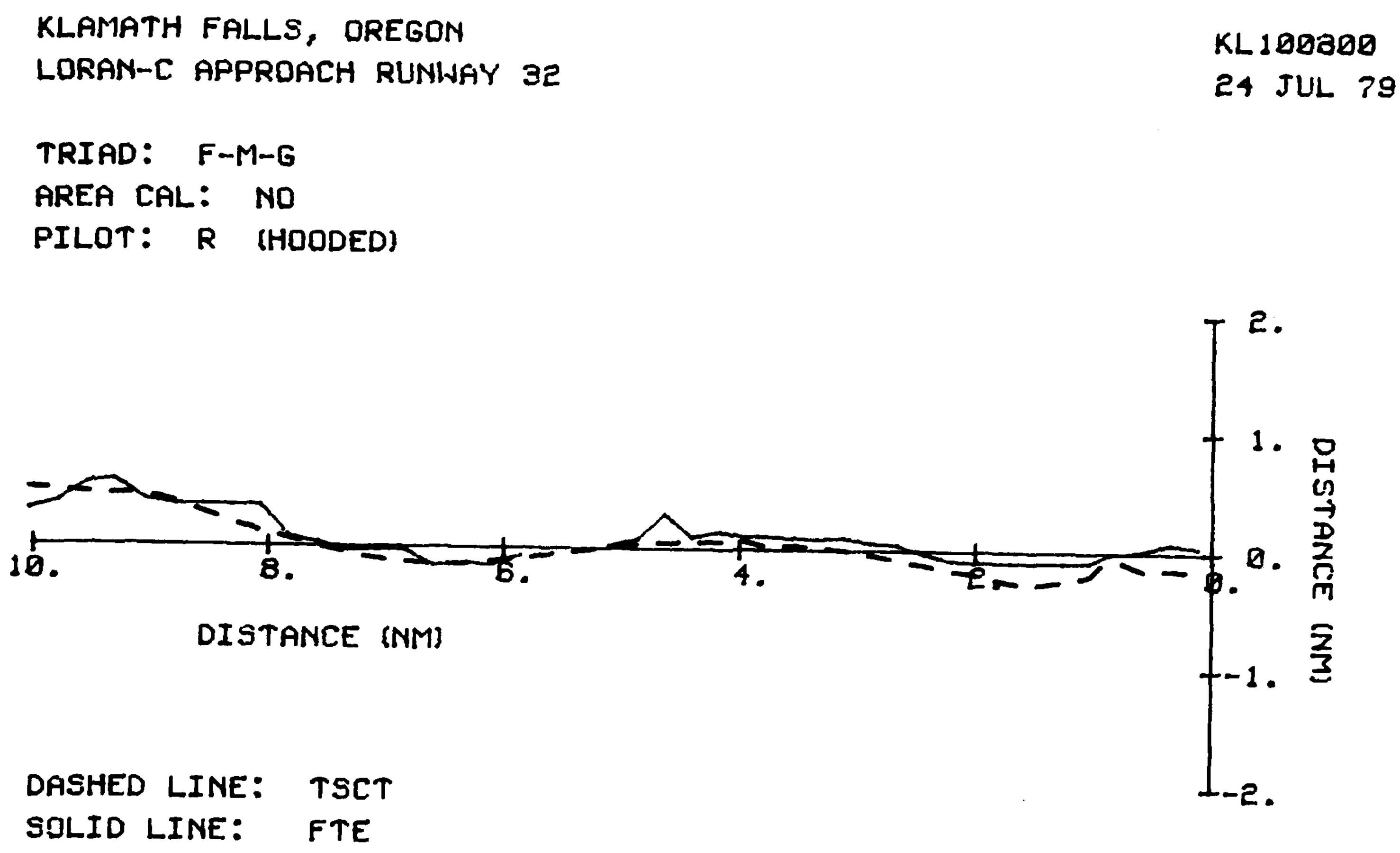


Figure A.6 Klamath Falls, Oregon Loran-C Approach Runway 32

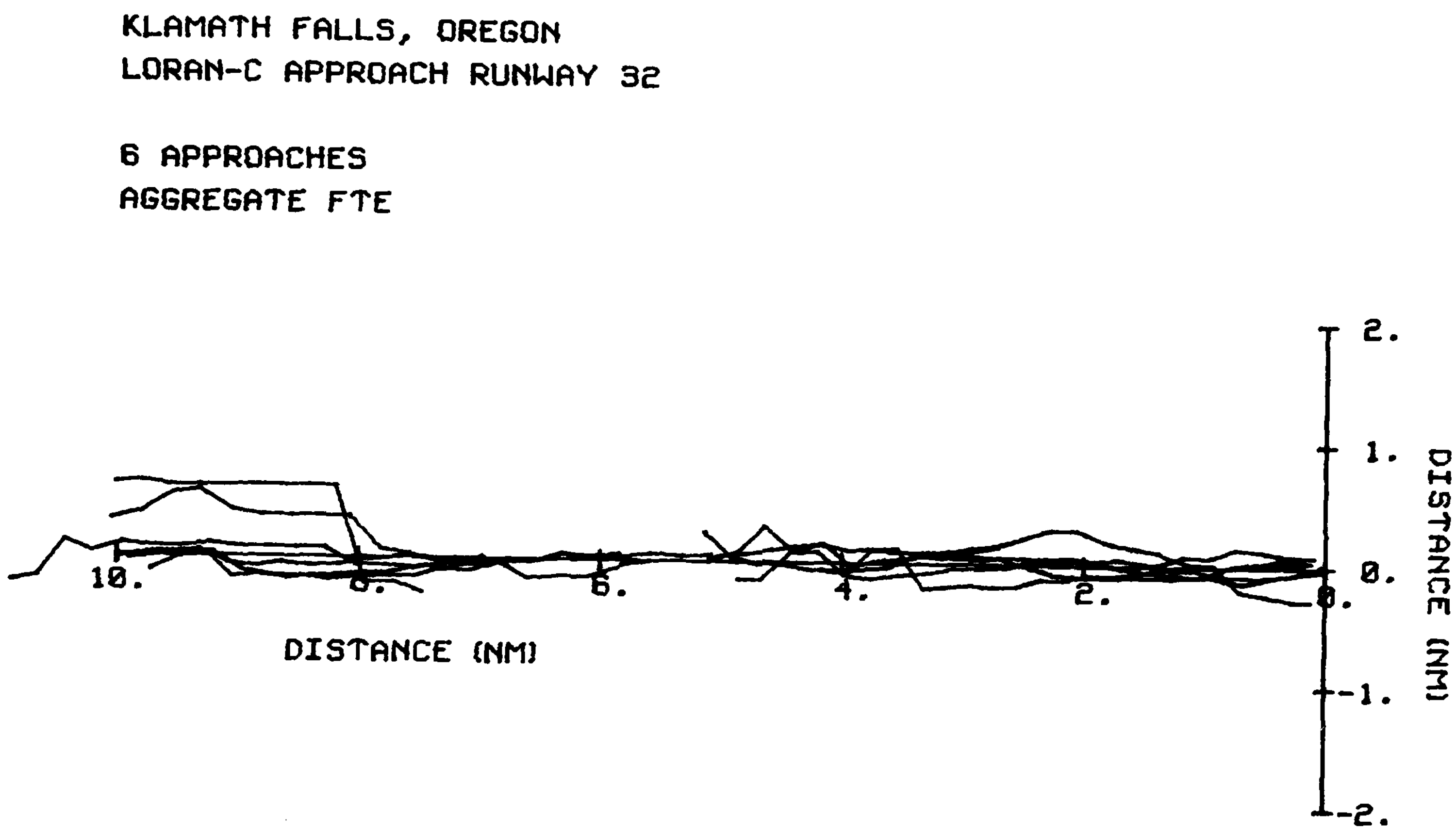


Figure A.7 Klamath Falls, Oregon Aggregate FTE

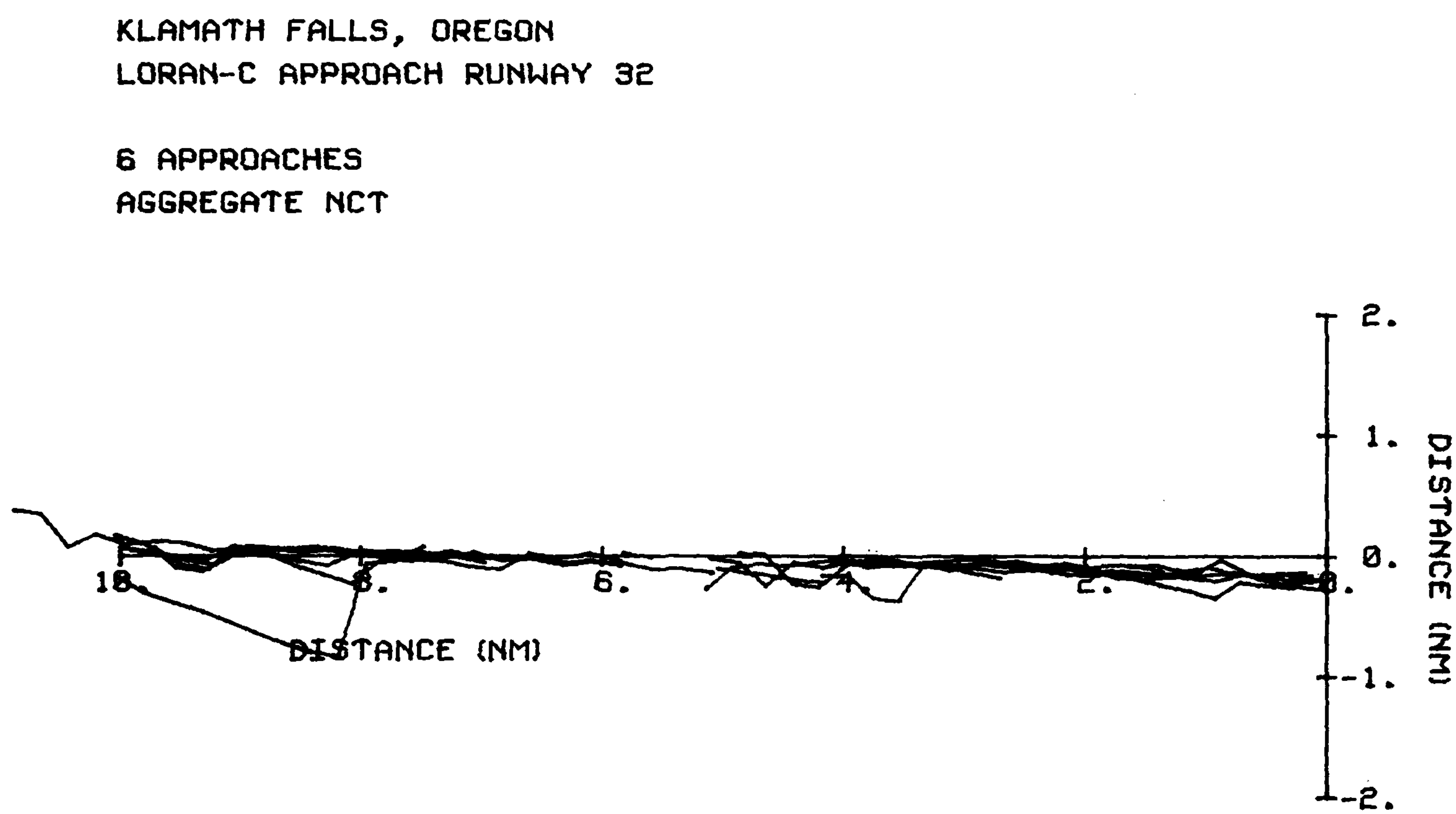


Figure A.8 Klamath Falls, Oregon Aggregate NCT

KLAMATH FALLS, OREGON
LORAN-C APPROACH RUNWAY 32

6 APPROACHES
AGGREGATE TSCT

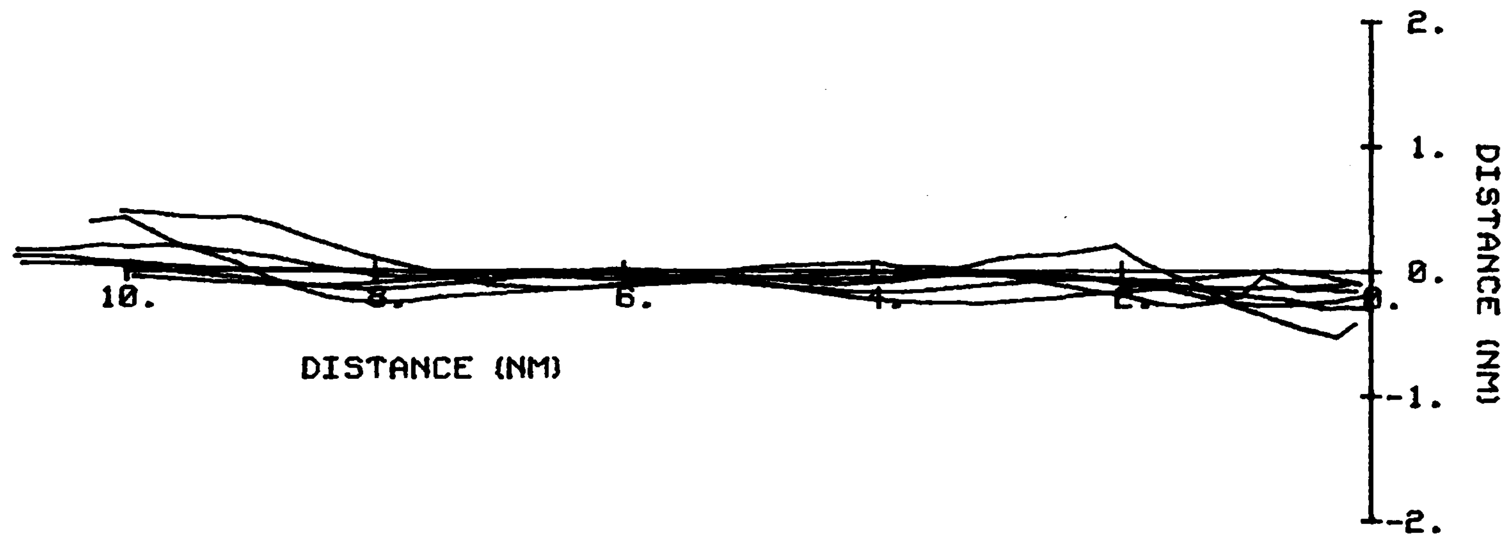
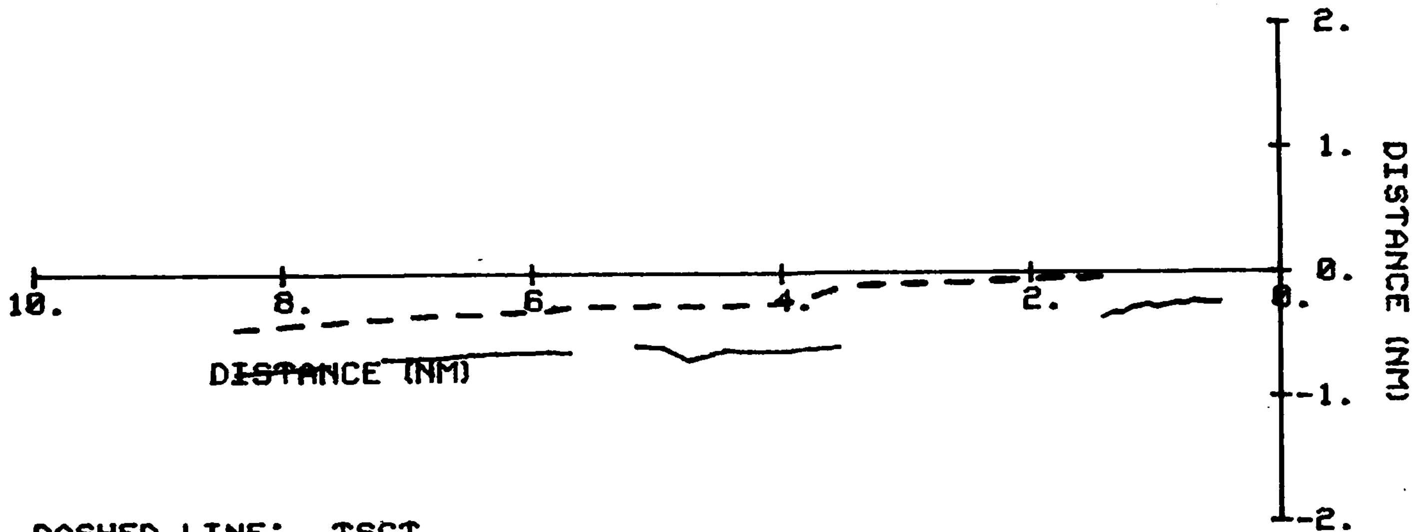


Figure A.9 Klamath Falls, Oregon Aggregate TSCT

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

L082239
7 JUL 79

TRIAD: F-M-G
AREA CAL: NO
PILOT: R (VISUAL)



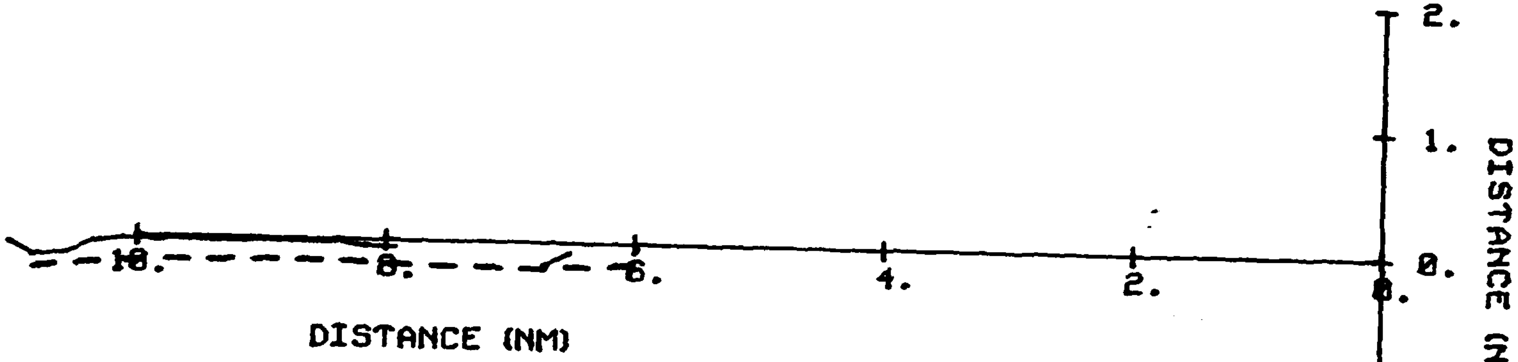
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.10 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

L083822
7 JUL 79

TRIAD: F-M-S
AREA CAL: NO
PILOT: R (HOODED)



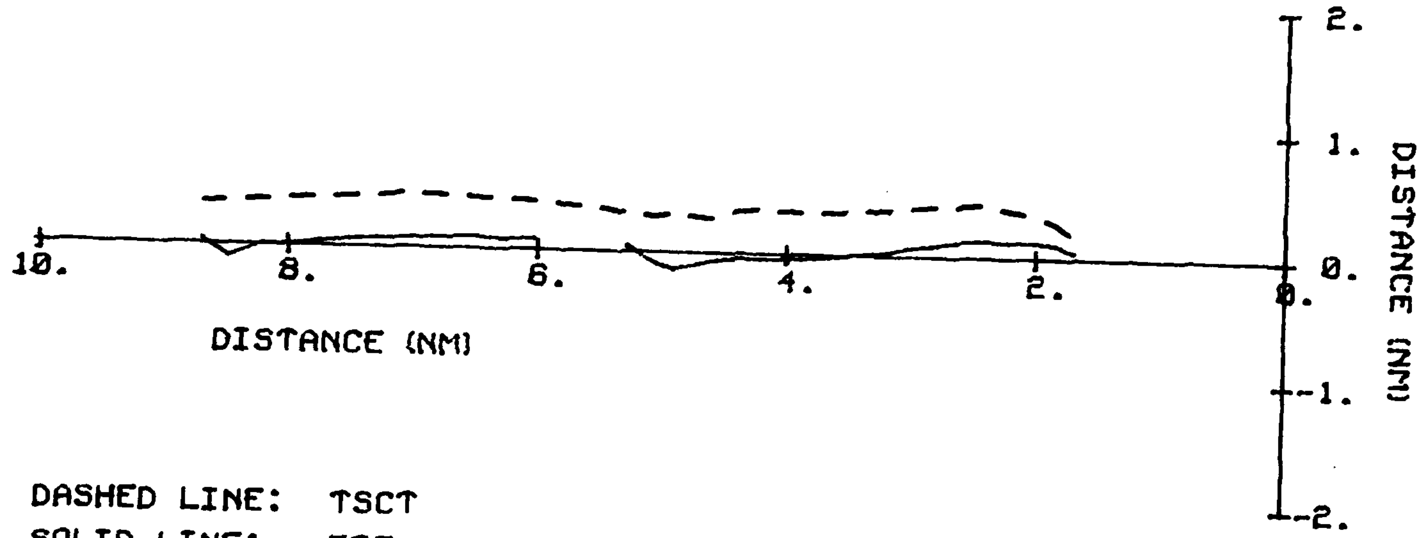
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.11 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT081254
26 JUL 79

TRIAD: F-M-S
AREA CAL: NO
PILOT: R (HOODED)



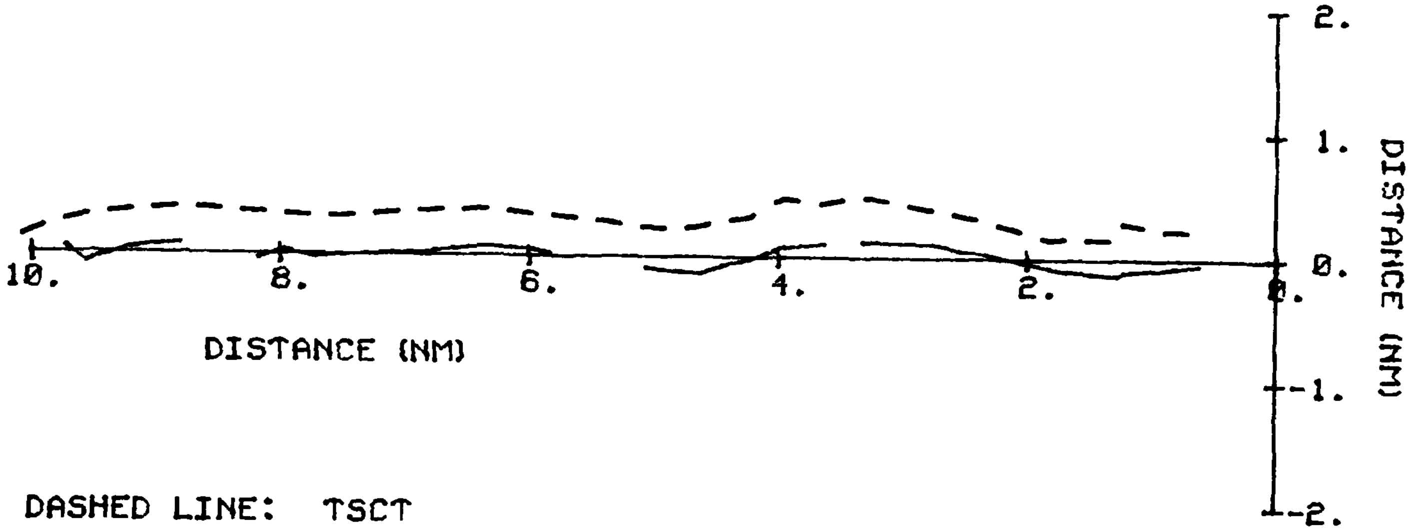
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.12 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT092931
26 JUL 79

TRIAD: F-M-S
AREA CAL: NO
PILOT: R (HOODED)



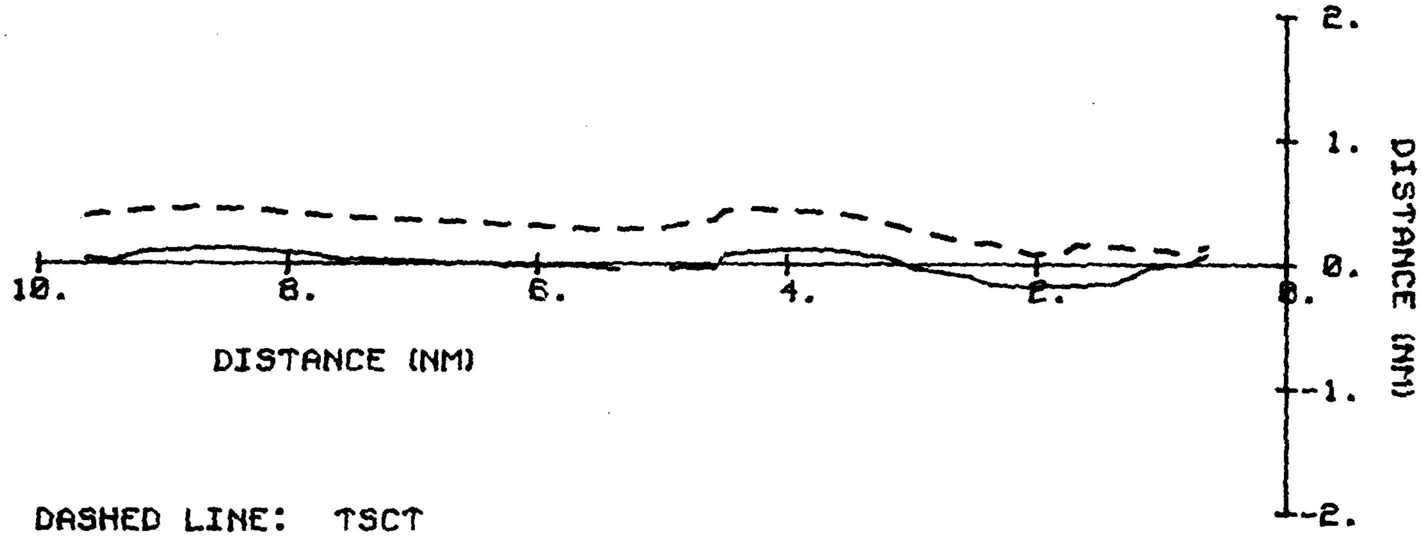
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.13 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT094644
26 JUL 79

TRIAD: F-M-S
AREA CAL: NO
PILOT: R (HOODED)



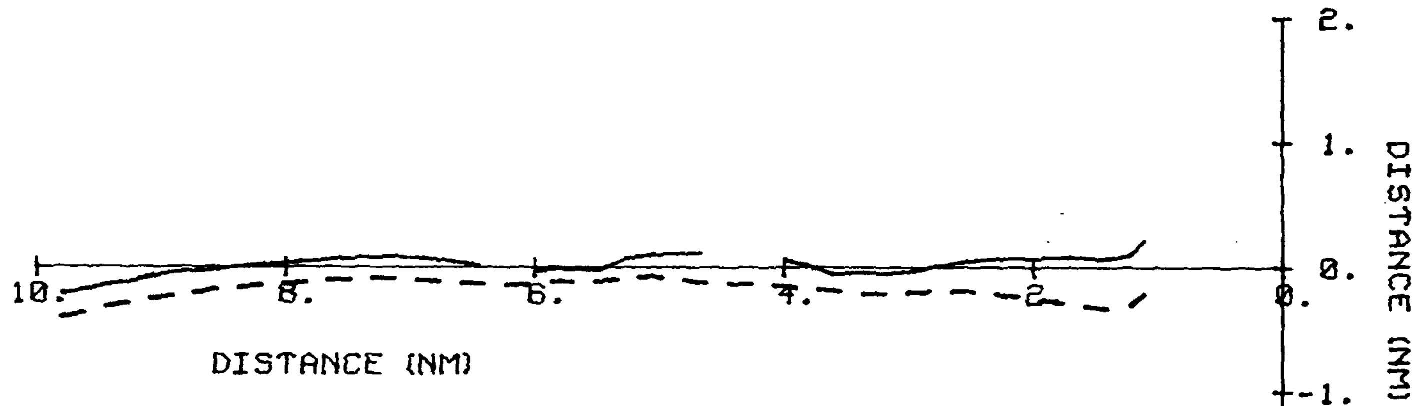
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.14 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT100257
26 JUL 79

TRIAD: F-M-G
AREA CAL: NO
PILOT: R (HOODED)



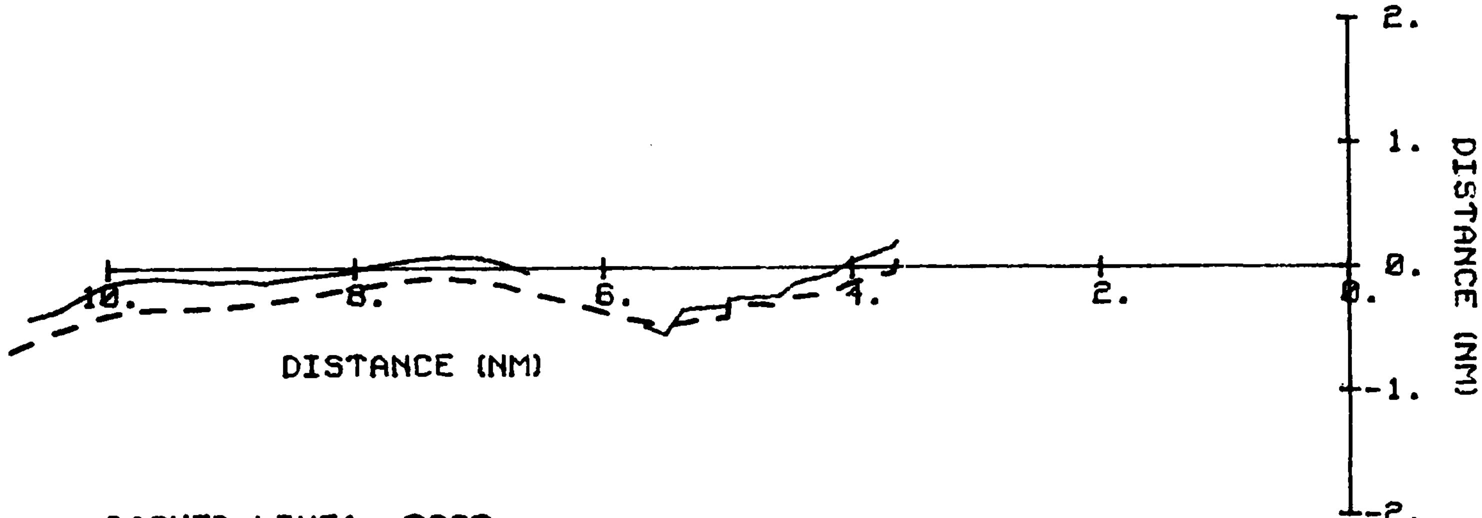
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.15 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT102646
26 JUL 73

TRIAD: F-M-G
AREA CAL: NO
PILOT: R (HOODED)



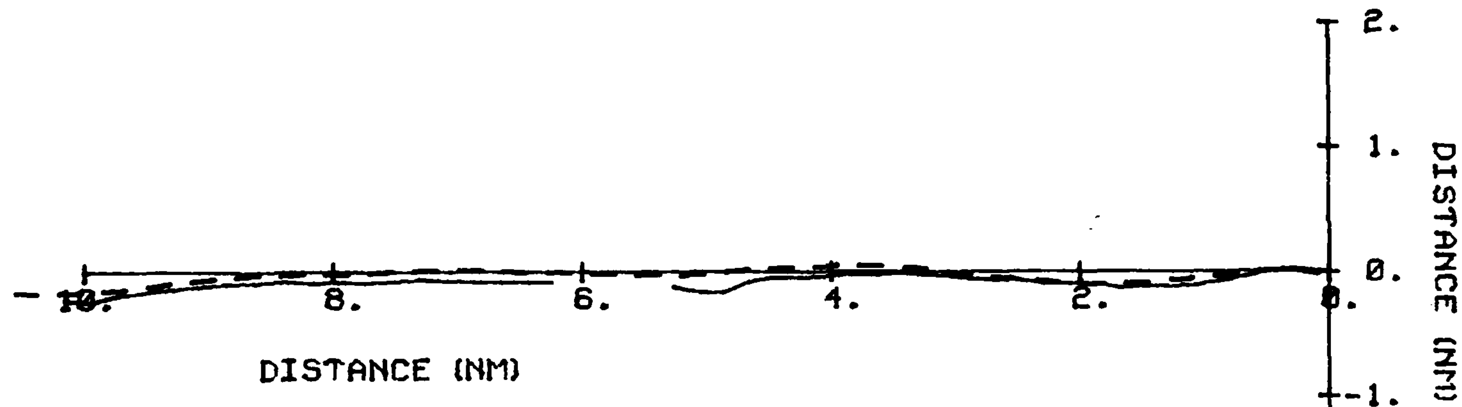
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.16 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT113014
26 JUL 79

TRIAD: F-M-G
AREA CAL: YES
PILOT: S (HOODED)



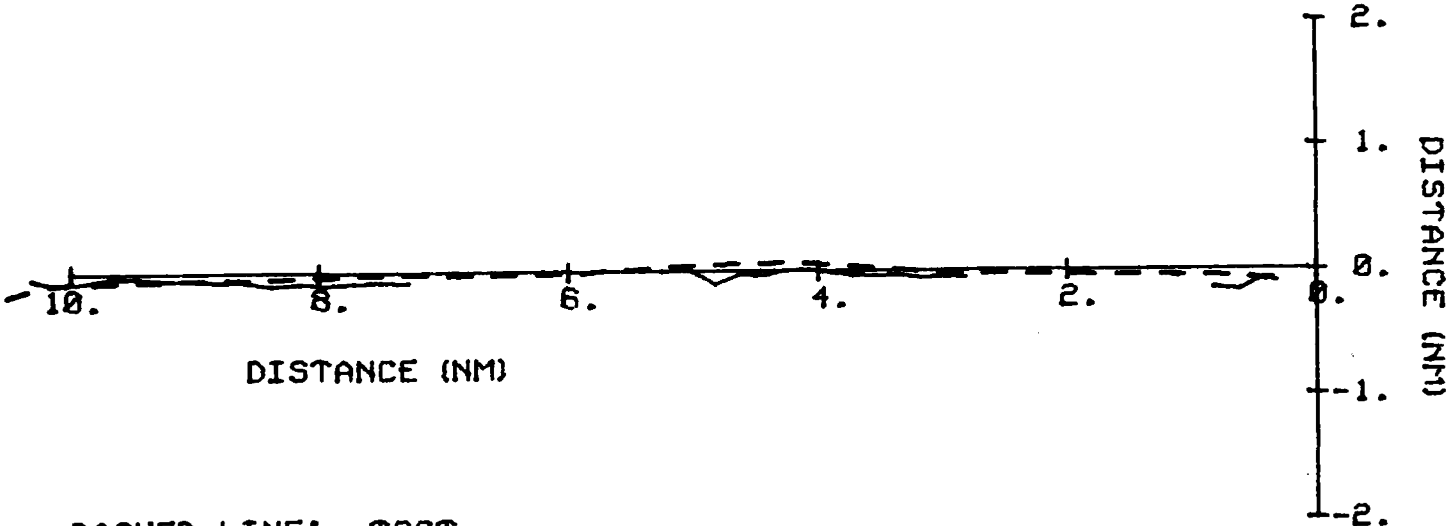
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.17 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT114651
26 JUL 79

TRIAD: F-M-G
AREA CAL: YES
PILOT: S (HOODED)



DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.18 South Lake Tahoe, California Loran-C Approach Runway 18

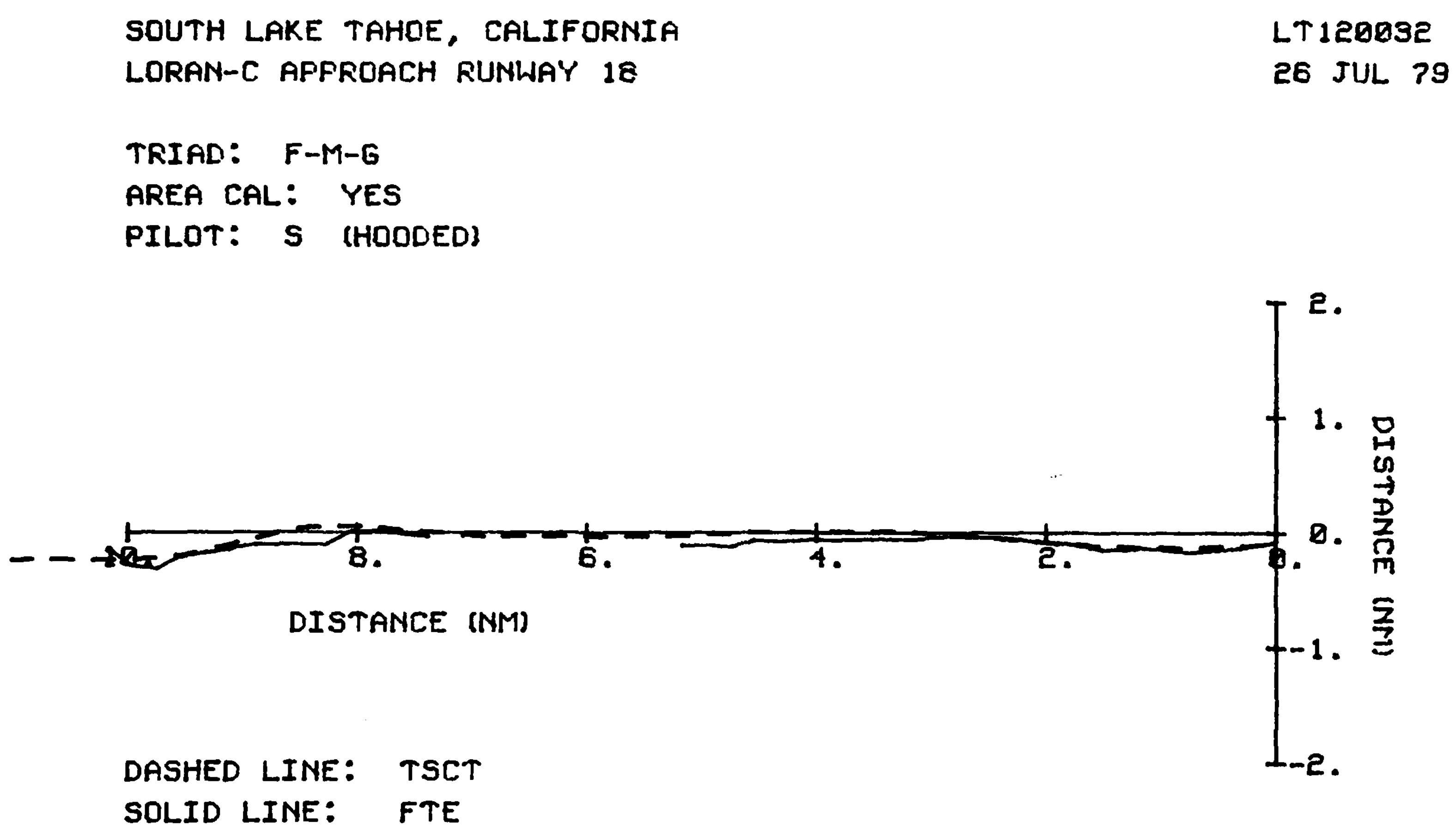
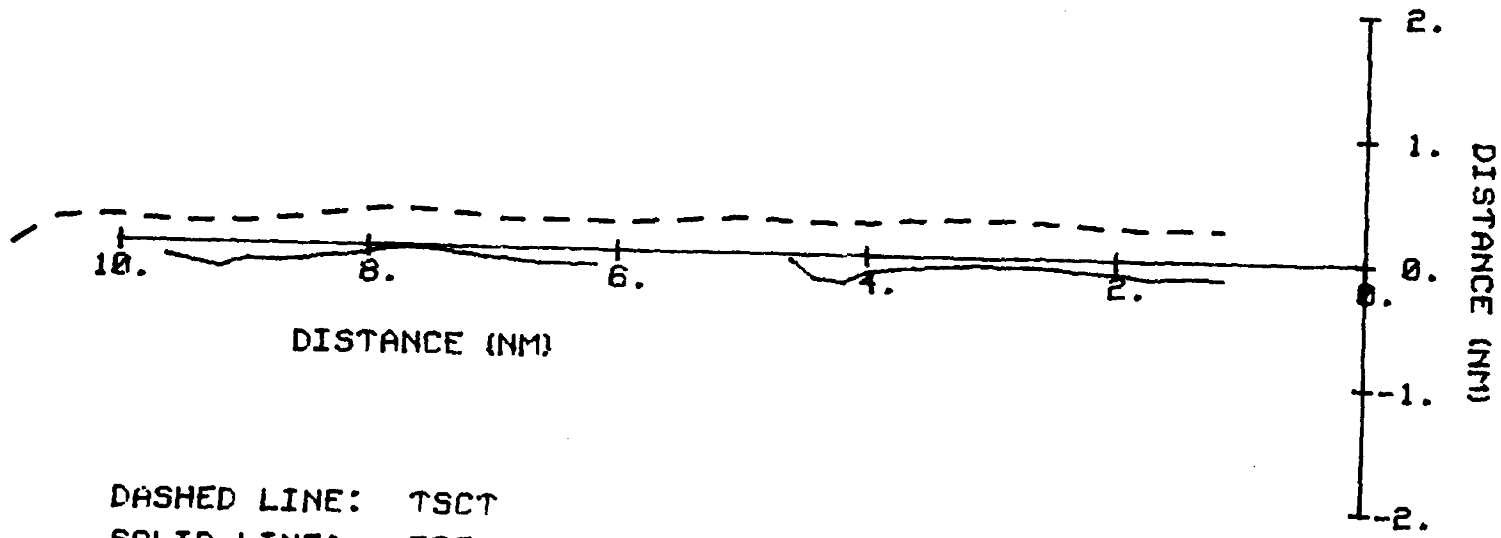


Figure A.19 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT121616
26 JUL 79

TRIAD: F-M-S
AREA CAL: NO
PILOT: S (HOODED)



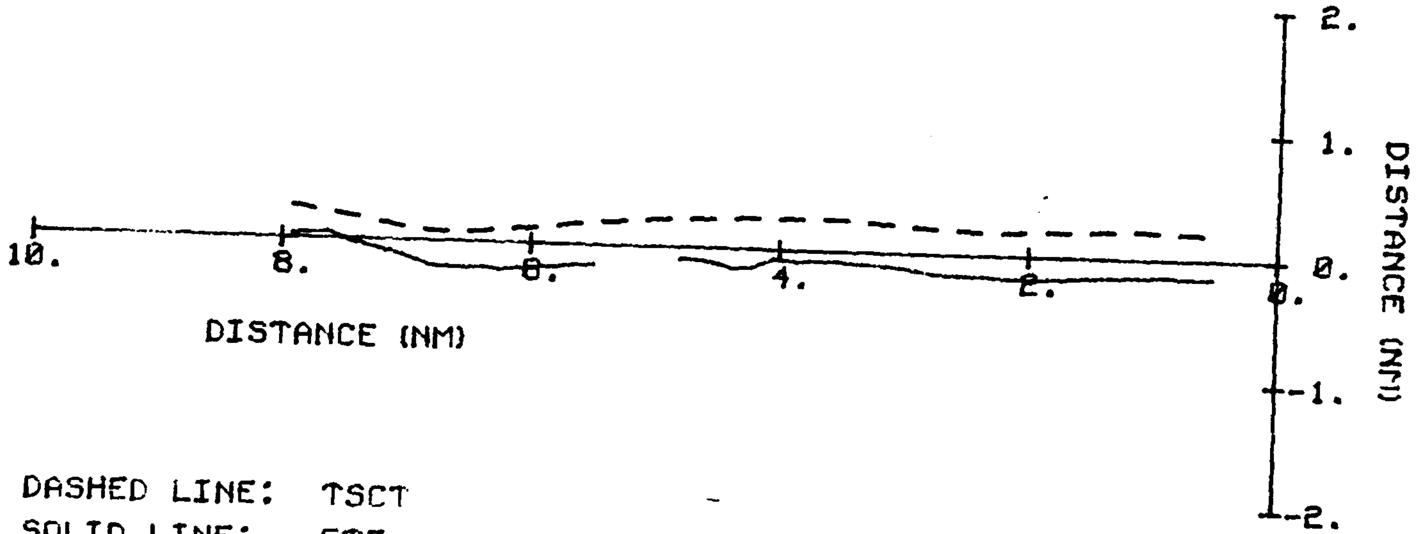
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.20 South Lake Tahoe, California Loran-C Approach Runway 18

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

LT123106
26 JUL 73

TRIAD: F-M-S
AREA CAL: NO
PILOT: S (HOODED)



DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.21 South Lake Tahoe, California Loran-C Approach Runway 18

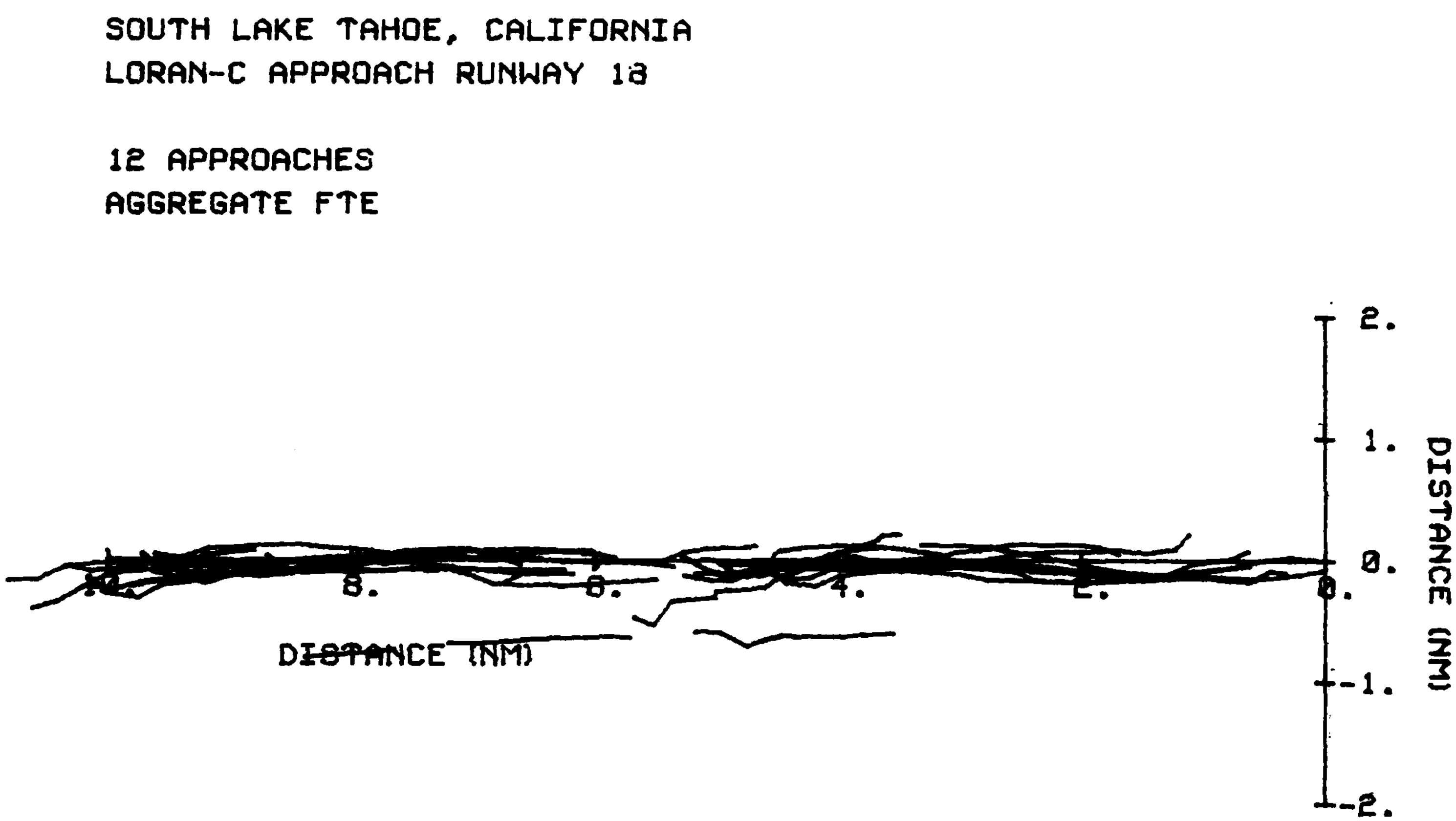


Figure A.22 South Lake Tahoe, California Aggregate FTE

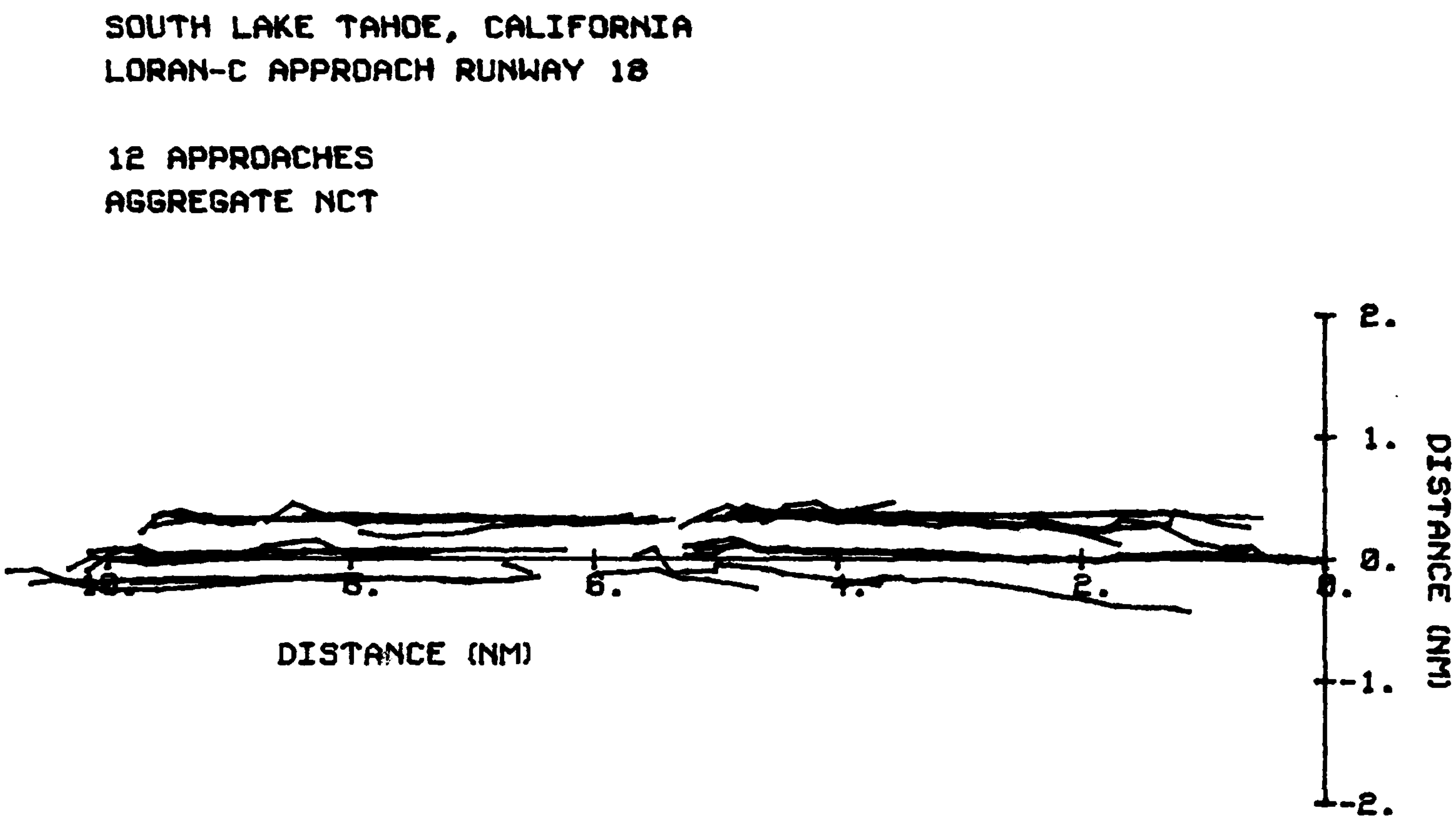


Figure A.23 South Lake Tahoe, California Aggregate NCT

SOUTH LAKE TAHOE, CALIFORNIA
LORAN-C APPROACH RUNWAY 18

12 APPROACHES
AGGREGATE TSCT

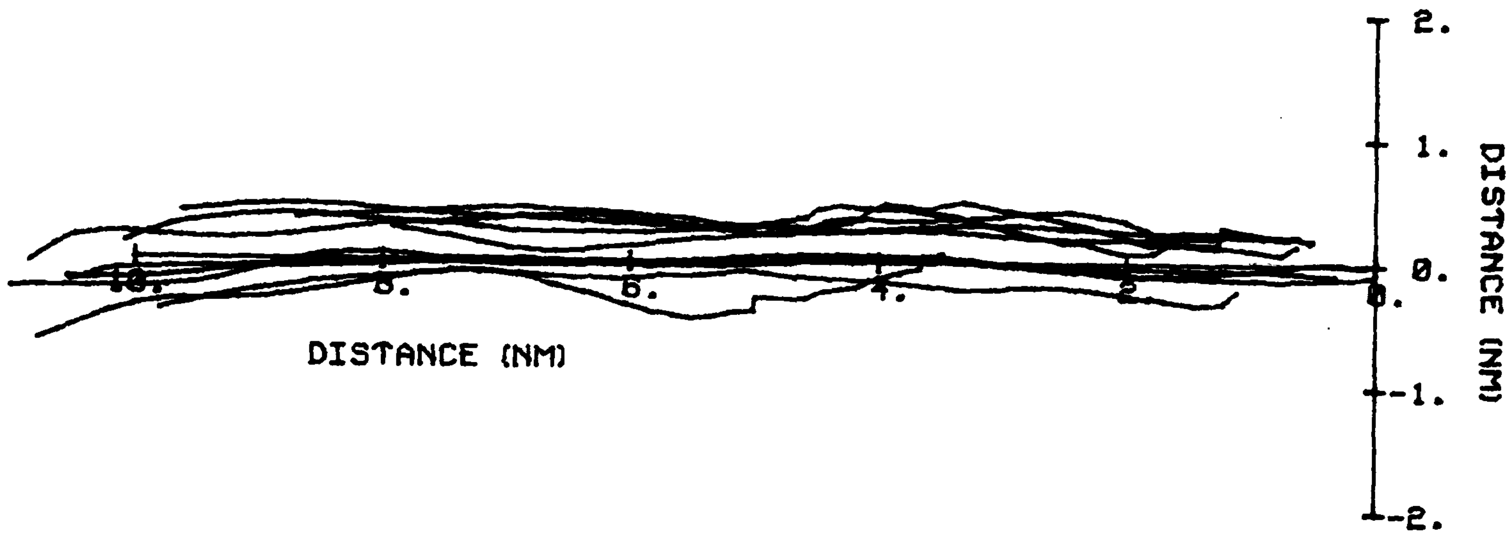
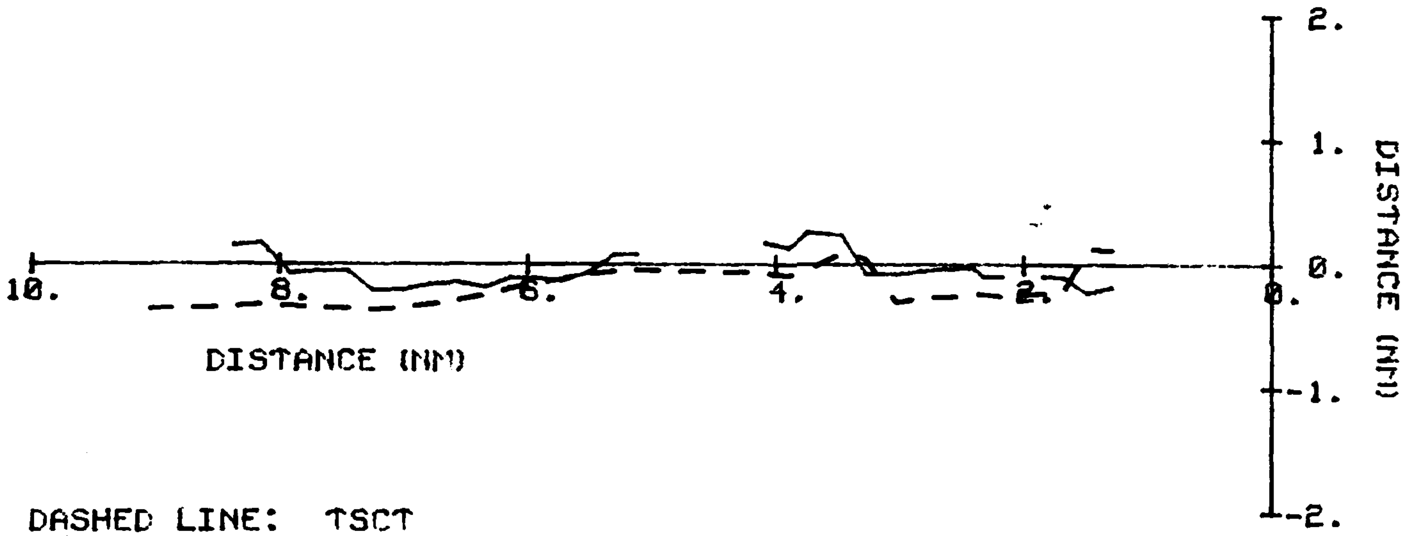


Figure A.24 South Lake Tahoe, California Aggregate TSCT

GRAND JUNCTION, COLORADO
LORAN-C APPROACH RUNWAY 11

GJ091012
28 JUL 79

TRIAD: F-M-G
AREA CAL: YES
PILOT: R (VISUAL)



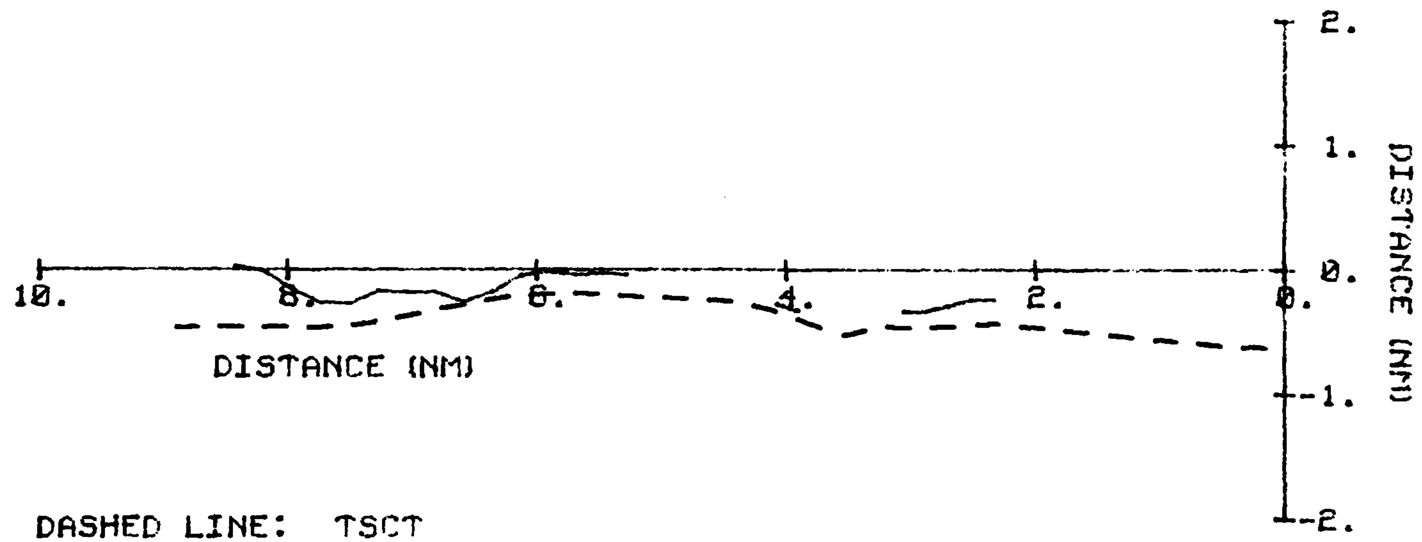
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.25 Grand Junction, Colorado Loran-C Approach Runway 11

GRAND JUNCTION, COLORADO
LORAN-C APPROACH RUNWAY 11

GJ032256
28 JUL 73

TRIAD: F-M-G
AREA CAL: YES
PILOT: R (HOODED)



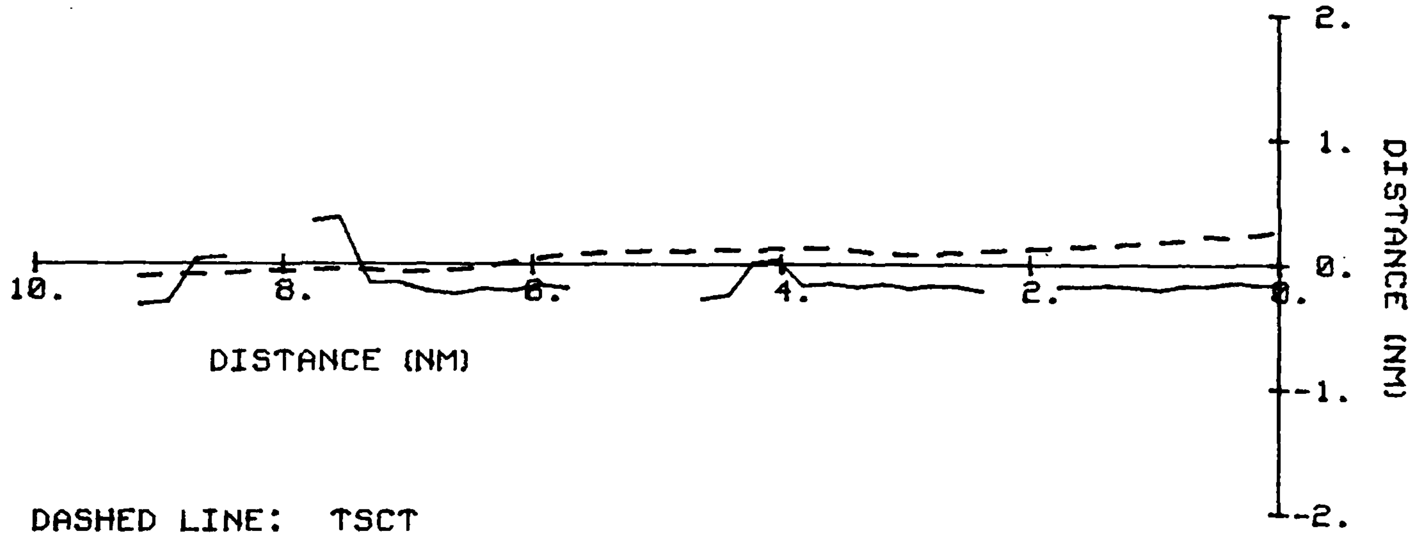
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.26 Grand Junction, Colorado Loran-C Approach Runway 11

GRAND JUNCTION, COLORADO
LORAN-C APPROACH RUNWAY 11

GJ093616
28 JUL 79

TRIAD: F-G-S
AREA CAL: NO
PILOT: R (VISUAL)



DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.27 Grand Junction, Colorado Loran-C Approach Runway 11

GRAND JUNCTION, COLORADO
LORAN-C APPROACH RUNWAY 11

3 APPROACHES
AGGREGATE FTE

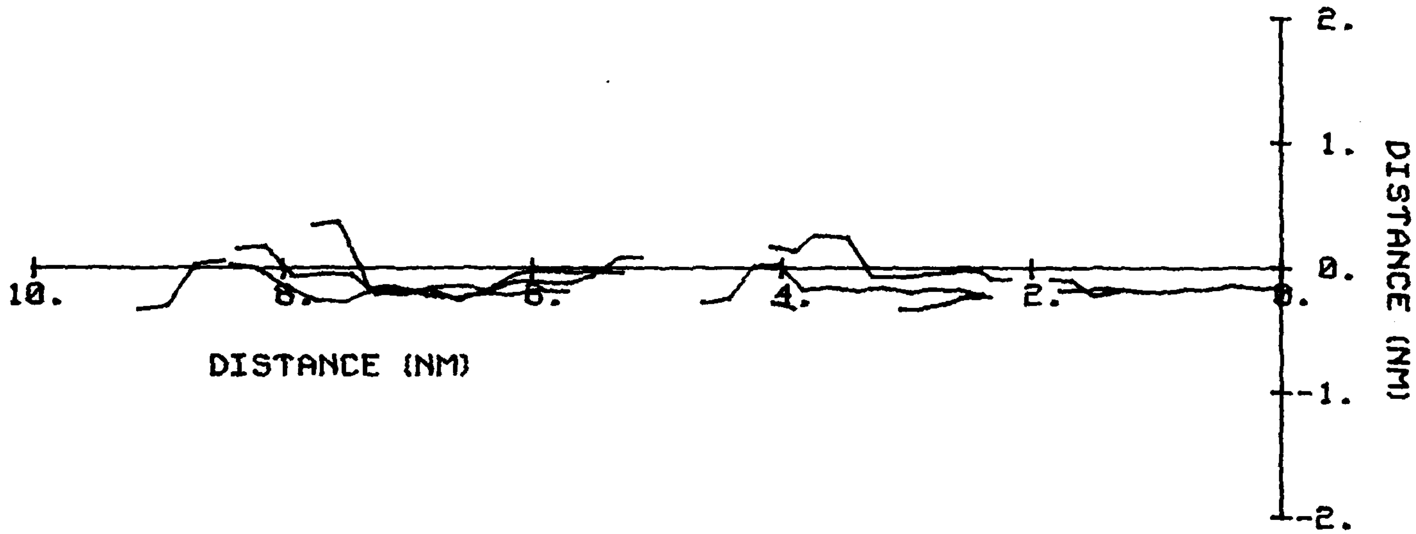


Figure A.28 Grand Junction, Colorado Aggregate FTE

GRAND JUNCTION, COLORADO
LORAN-C APPROACH RUNWAY 11

3 APPROACHES
AGGREGATE NCT

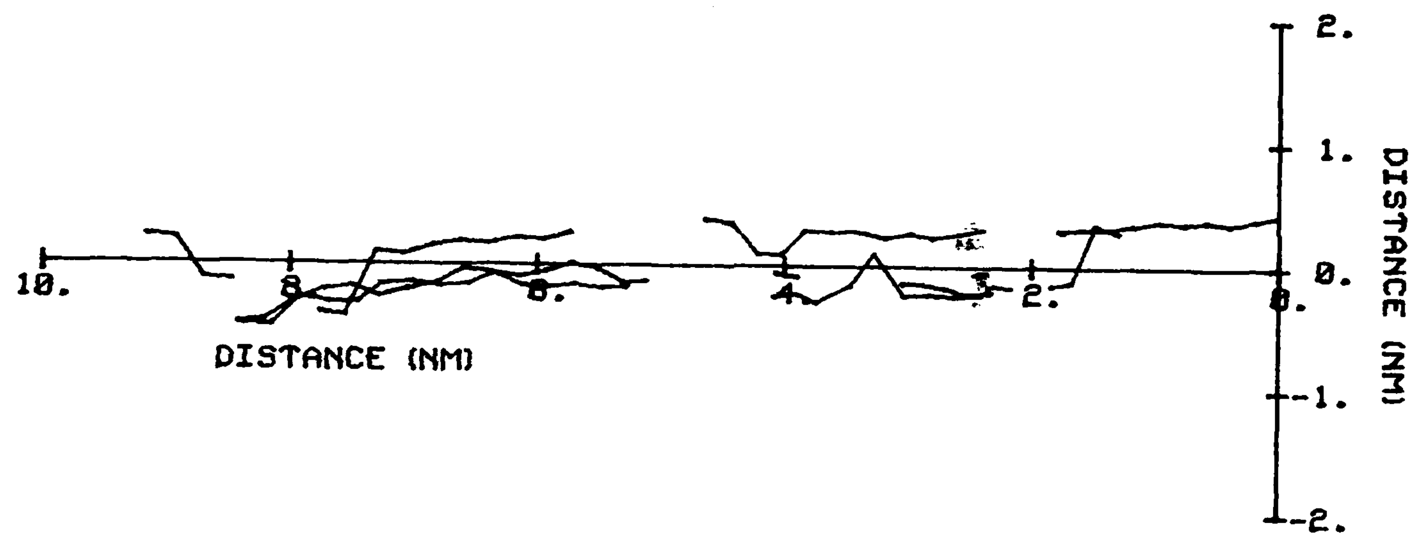


Figure A.29 Grand Junction, Colorado Aggregate NCT

GRAND JUNCTION, COLORADO
LORAN-C APPROACH RUNWAY 11

3 APPROACHES
AGGREGATE TSCT

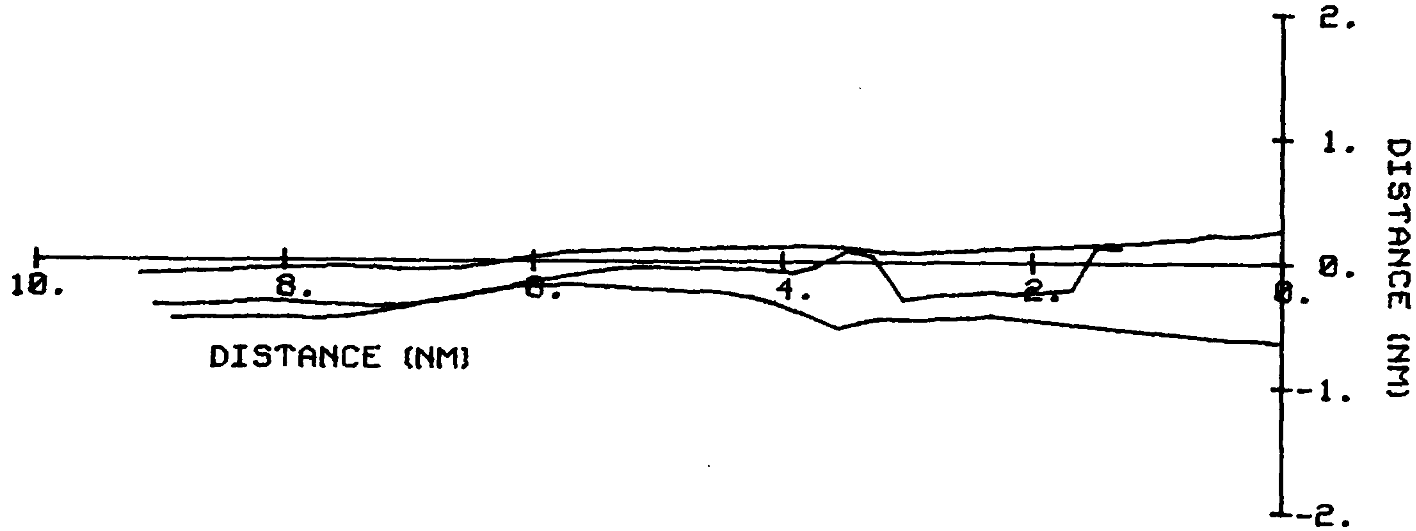


Figure A.30 Grand Junction, Colorado Aggregate TSCT

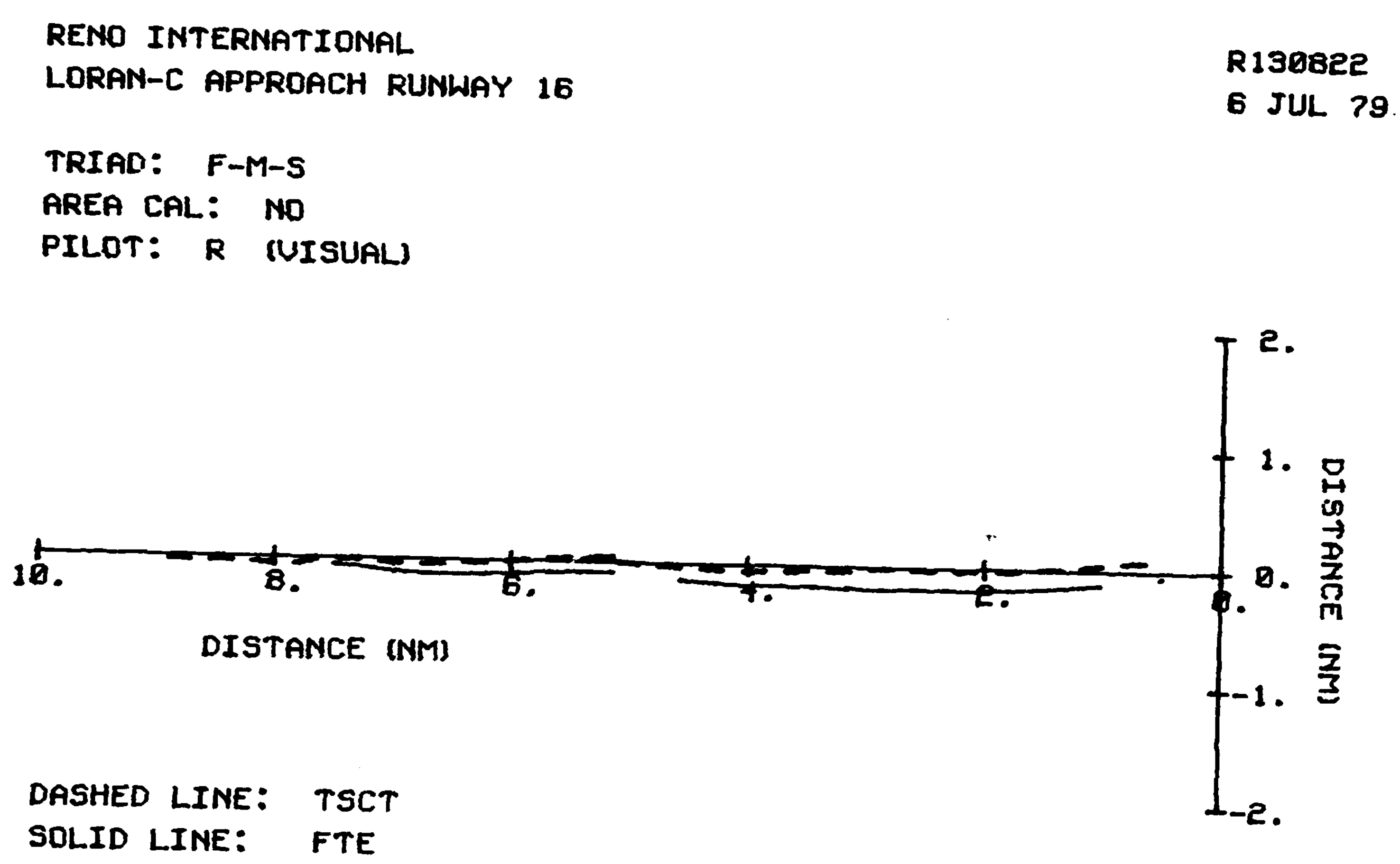
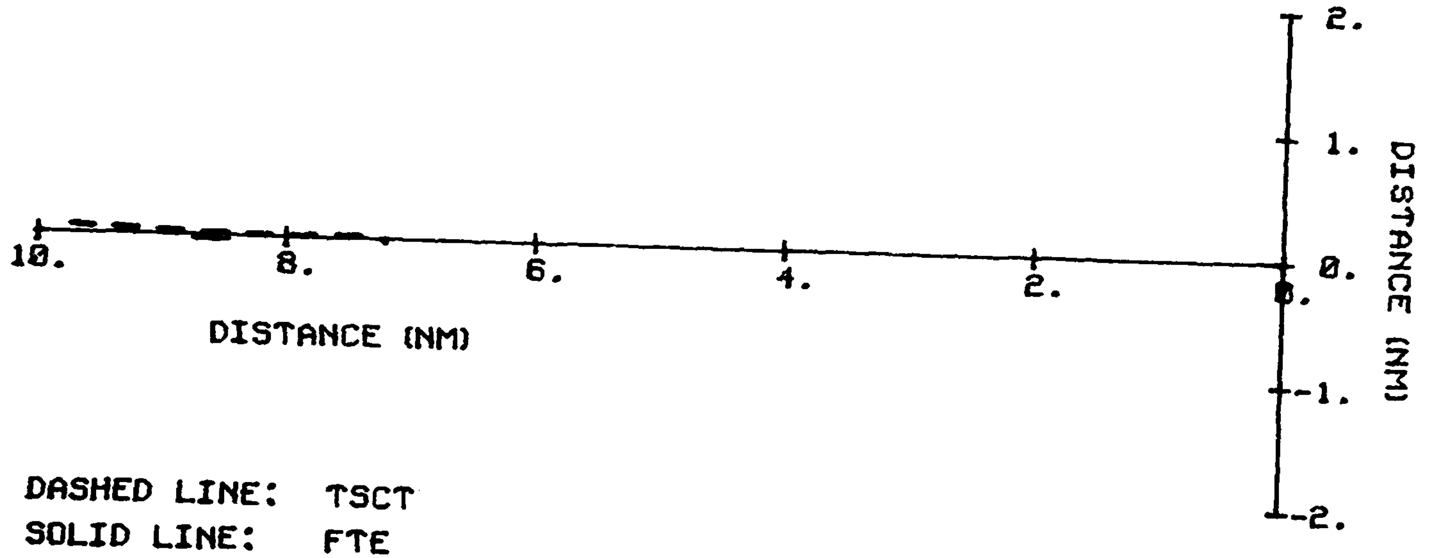


Figure A.31 Reno International Loran-C Approach Runway 16

[illegible] INTERNATIONAL
LORAN-C APPROACH RUNWAY 16

R132510
6 JUL 79

TRIAD: F-M-S
AREA CAL: NO
PILOT: R (VISUAL)



DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.32 Reno International Loran-C Approach Runway 16

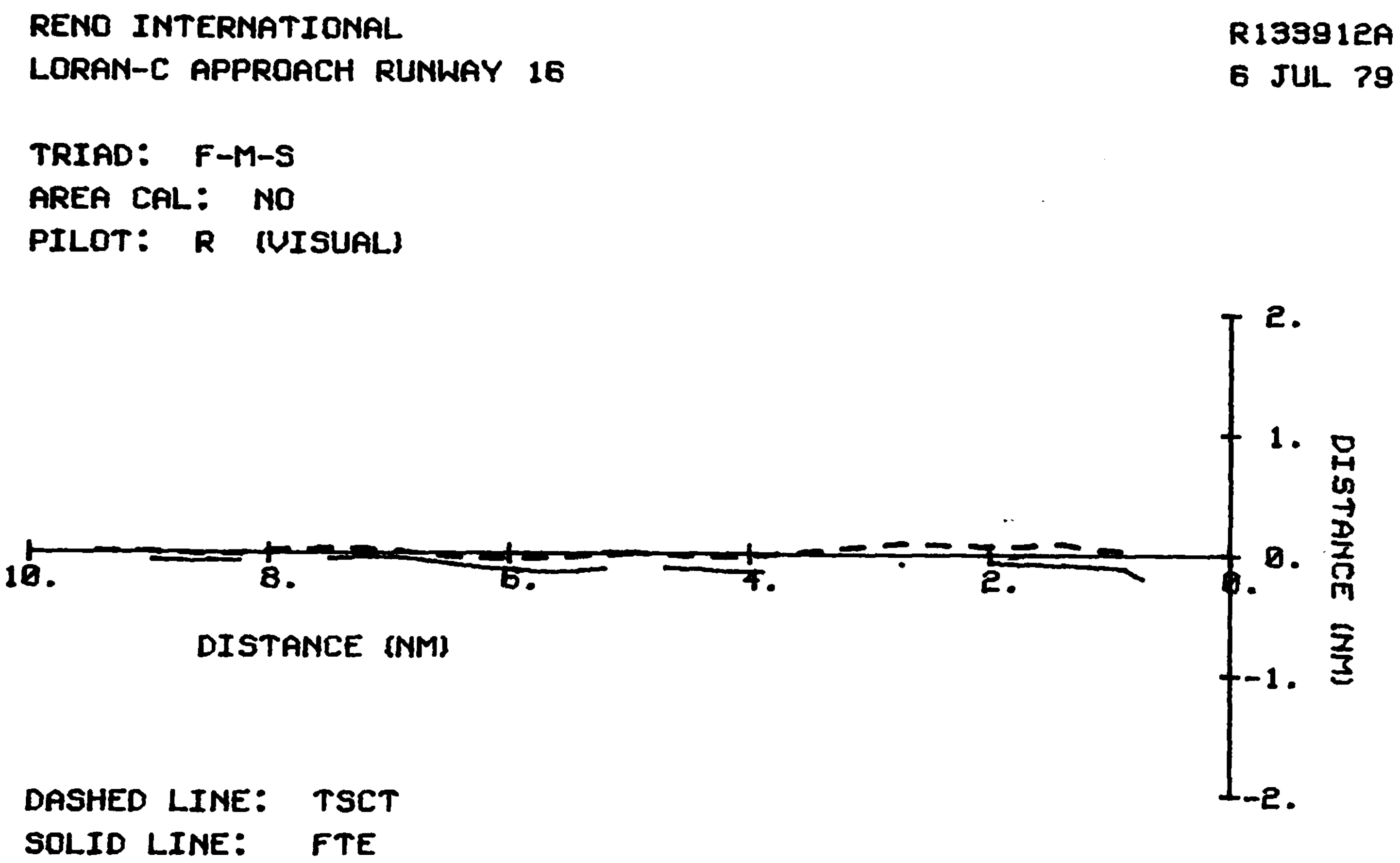


Figure A.33 Reno International Loran-C Approach Runway 16

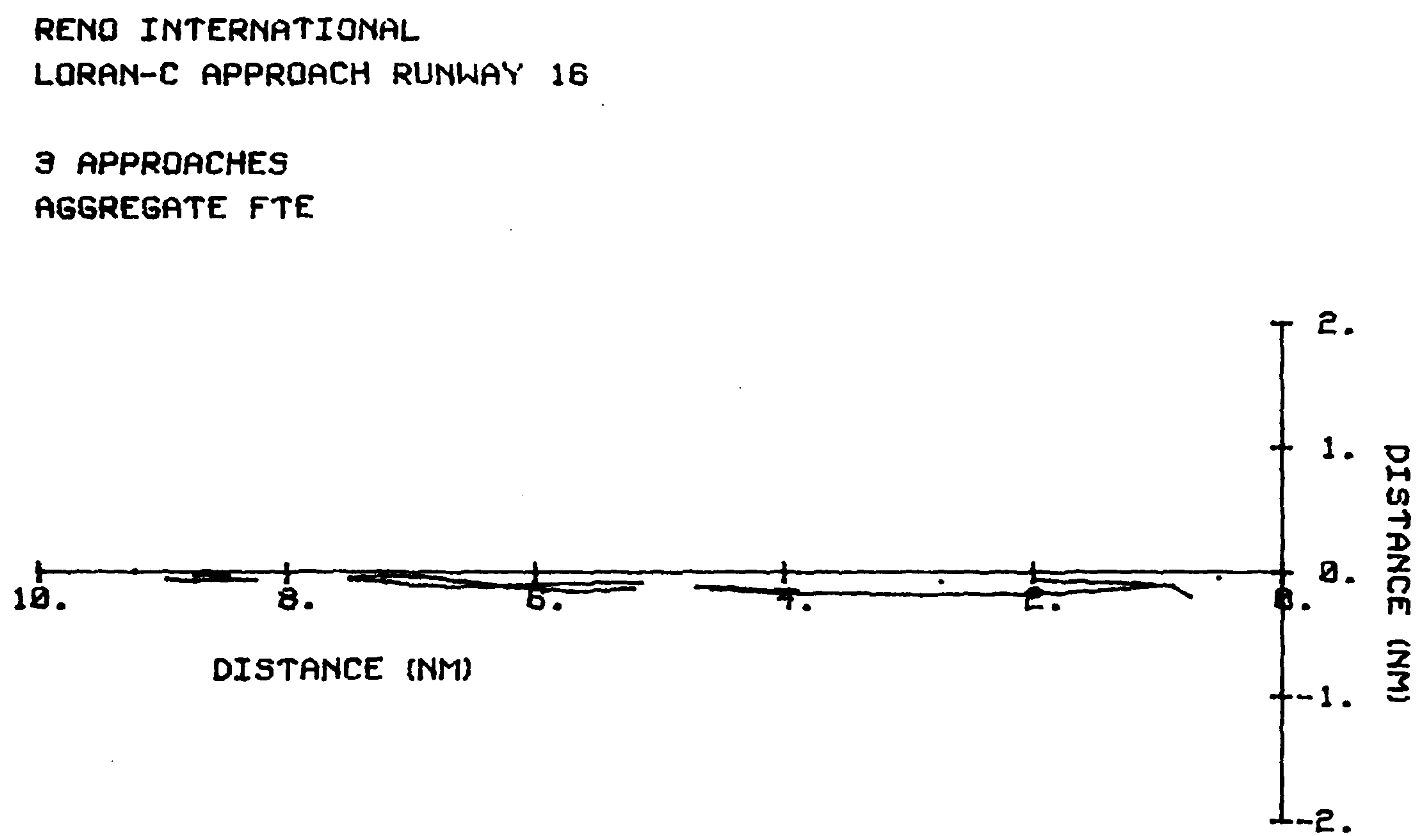


Figure A.34 Reno International Aggregate FTE

RENO INTERNATIONAL
LORAN-C APPROACH RUNWAY 16

3 APPROACHES
AGGREGATE NCT

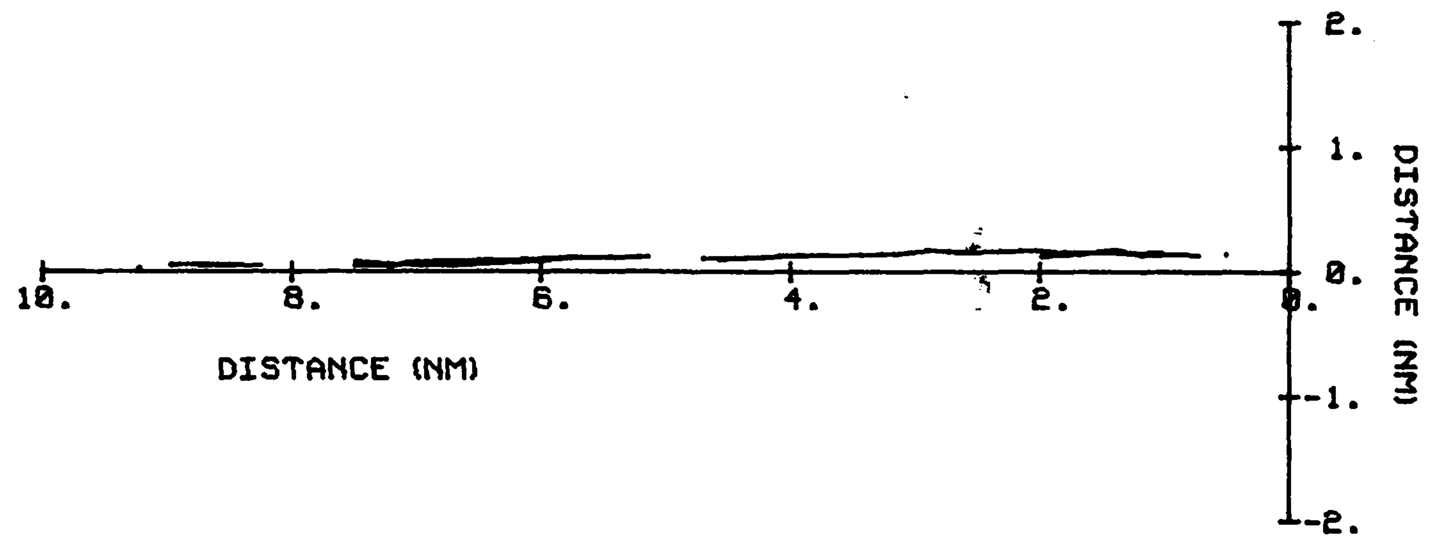


Figure A.35 Reno International Aggregate NCT

RENO INTERNATIONAL
LORAN-C APPROACH RUNWAY 16

3 APPROACHES
AGGREGATE TSCT

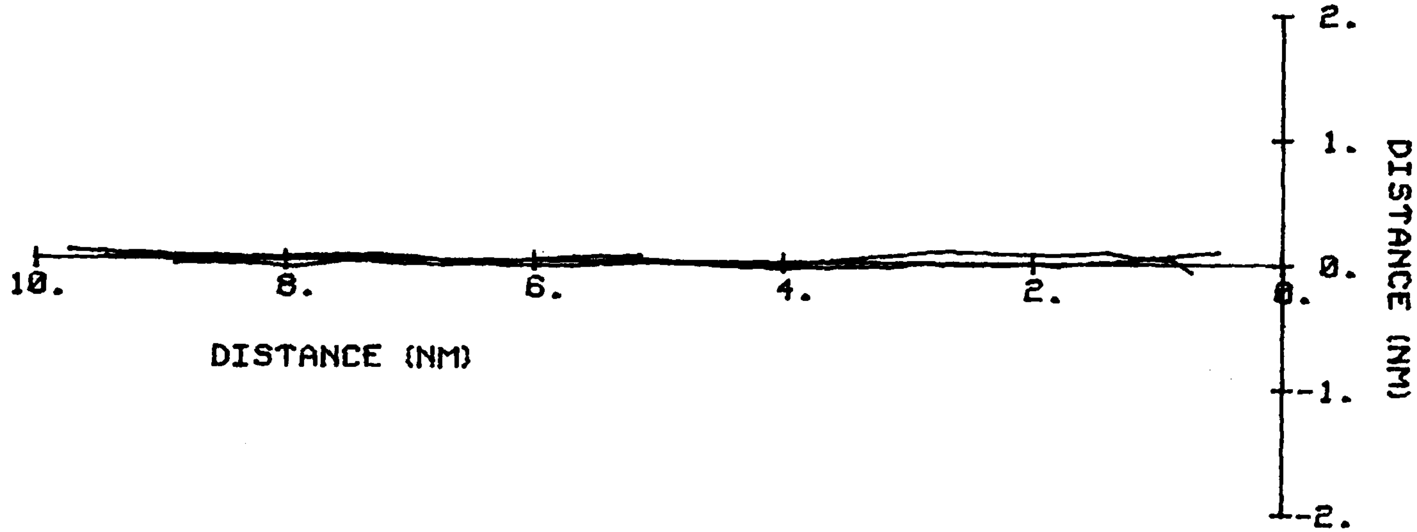
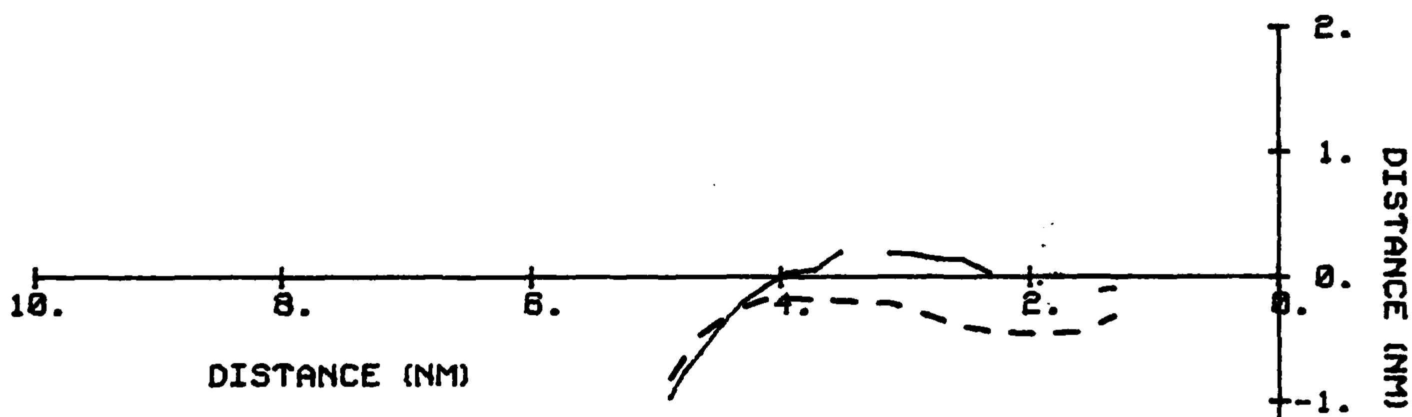


Figure A.36 Reno International Aggregate TSCT

RENO/STEAD
LORAN-C TRACKING RUN RUNWAY 26

S170947
21 JUL 79

TRIAD: F-M-G
AREA CAL: NO
PILOT: R (VISUAL)



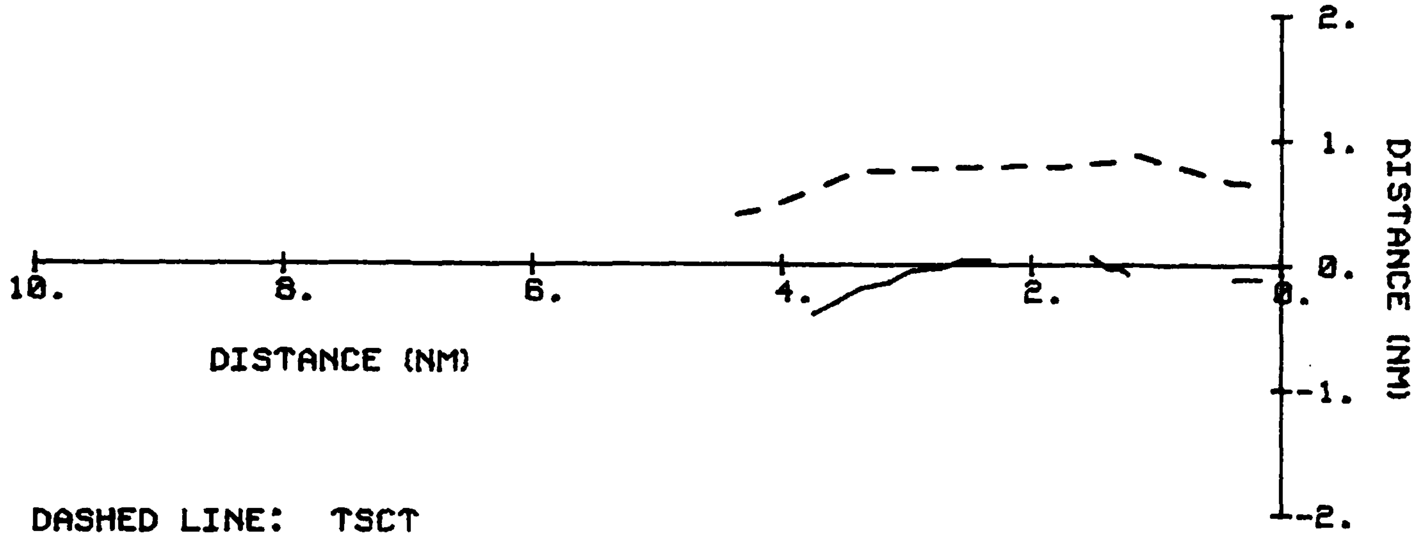
DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.37 Reno/Stead Tracking Run Runway 26

RENO/STEAD
LORAN-C TRACKING RUN RUNWAY 26

S171529
21 JUL 79

TRIAD: F-M-S
AREA CAL: NO
PILOT: R (VISUAL)



DASHED LINE: TSCT
SOLID LINE: FTE

Figure A.38 Reno/Stead Tracking Run Runway 26

RENO/STEAD
LORAN-C TRACKING RUN RUNWAY 26

2 APPROACHES
AGGREGATE FTE

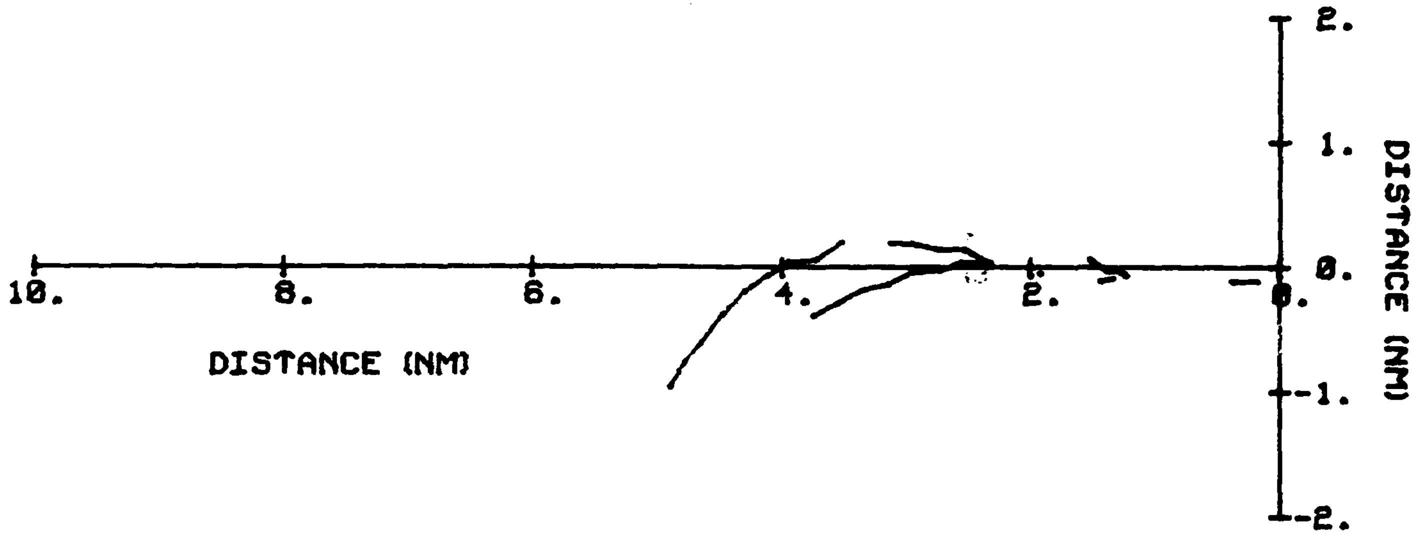


Figure A.39 Reno/Stead Aggregate FTE

RENO/STEAD
LORAN-C TRACKING RUN RUNWAY 26

2 APPROACHES
AGGREGATE NCT

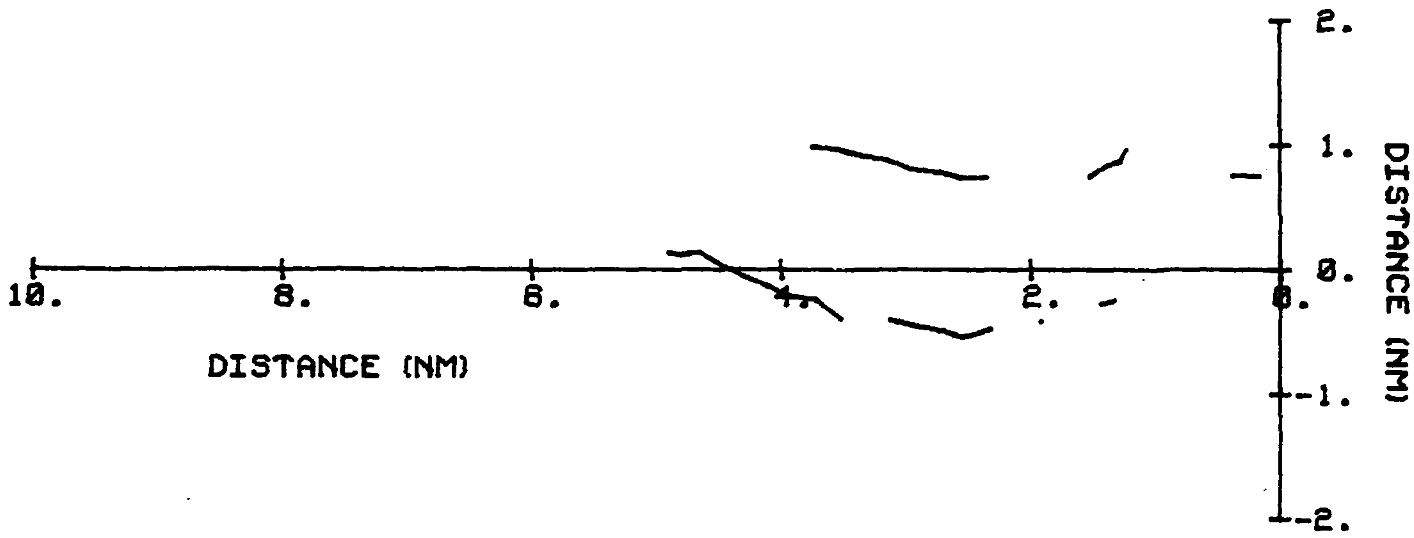


Figure A.40 Reno/Stead Aggregate NCT

RENO/STEAD
LORAN-C TRACKING RUN RUNWAY 26

2 APPROACHES
AGGREGATE TSCT

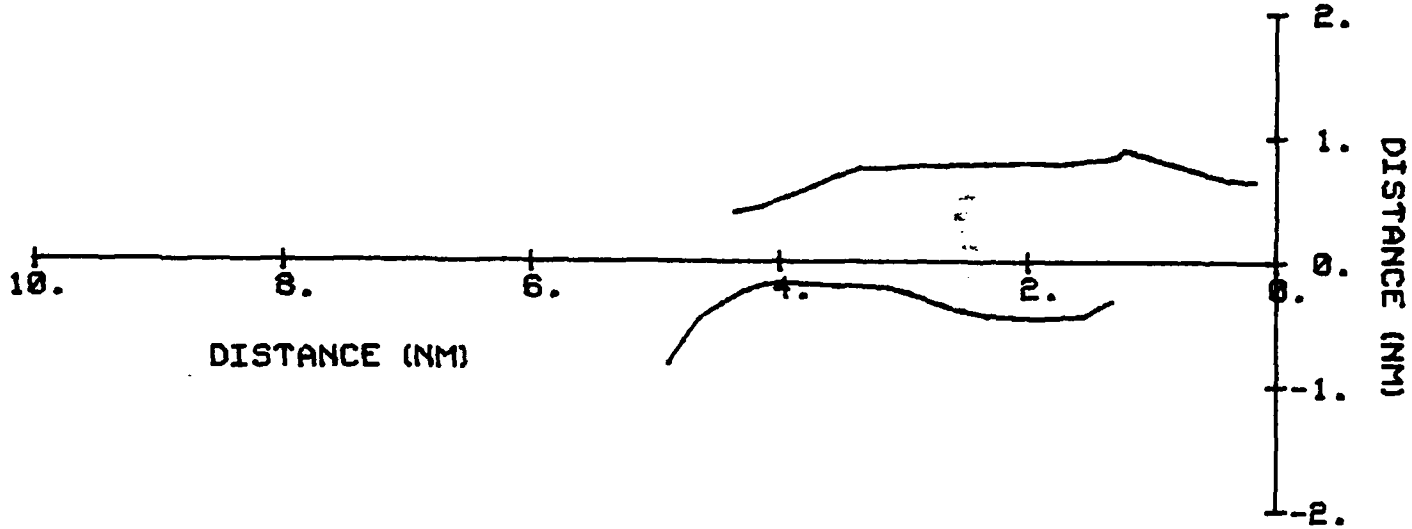


Figure A.41 Reno/Stead Aggregate TSCT

APPENDIX B

LORAN-C TIME DIFFERENCE ERROR PLOTS

Plots of the aggregate Loran-C time difference error for the approaches flown during the test are presented in this appendix. These data are comparisons of time difference data recorded from the RDU data bus with time difference values computed using the RAPPS position data according to the procedures described in Section 6.0. The distance is relative to the missed approach point. The plots denote the following locations and station pairs:

1) South Lake Tahoe California
   - B.1 George-Fallon
   - B.2 Middletown-Fallon
   - B.3 Searchlight-Fallon
2) Reno International*
   - B.4 Middletown-Fallon
   - B.5 Searchlight-Fallon
3) Reno Stead
   - B.6 George-Fallon
   - B.7 Middletown-Fallon
   - B.8 Searchlight-Fallon
4) Klamath Falls, Oregon
   - B.9 George-Fallon
   - B.10 Middletown-Fallon
   - B.11 Searchlight-Fallon
5) Grand Junction, Colorado
   - B.12 George-Fallon
   - B.13 Middletown-Fallon
   - B.14 Searchlight-Fallon

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*George-Fallon was not used.

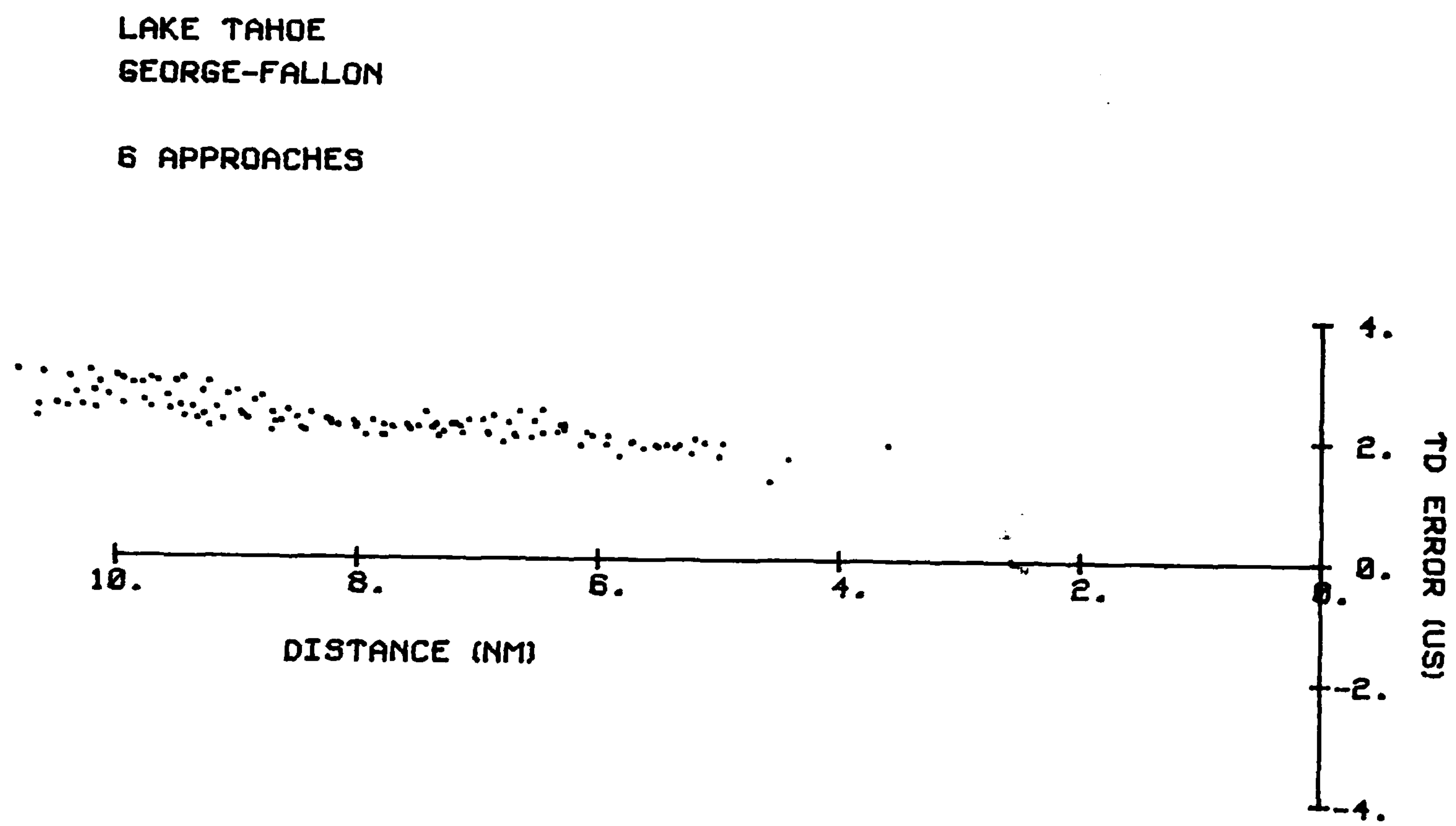


Figure B.1 Time Difference Error at Lake Tahoe for the George-Fallon Stations

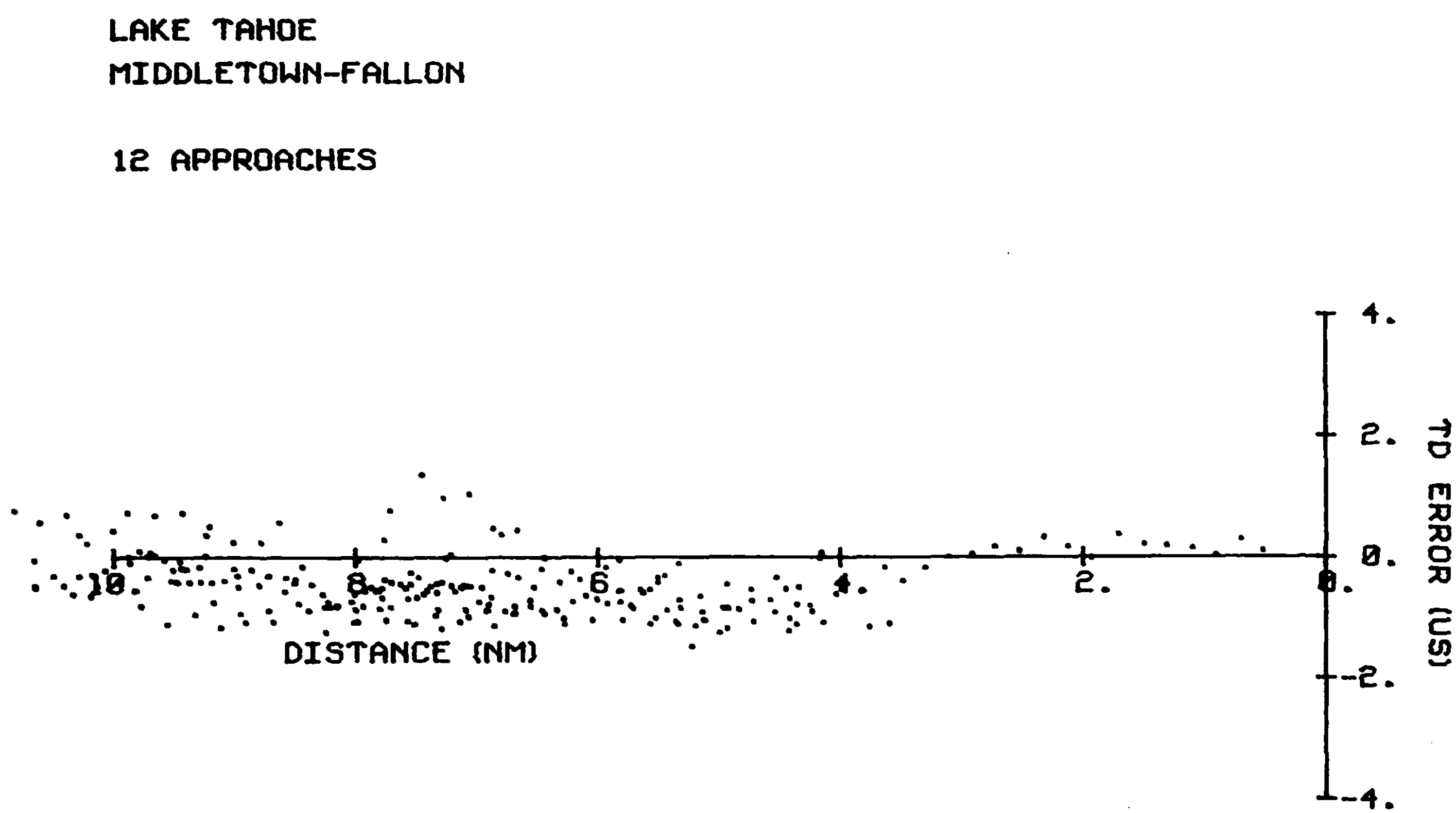


Figure B.2 Time Difference Error at Lake Tahoe for the Middletown-Fallon Stations

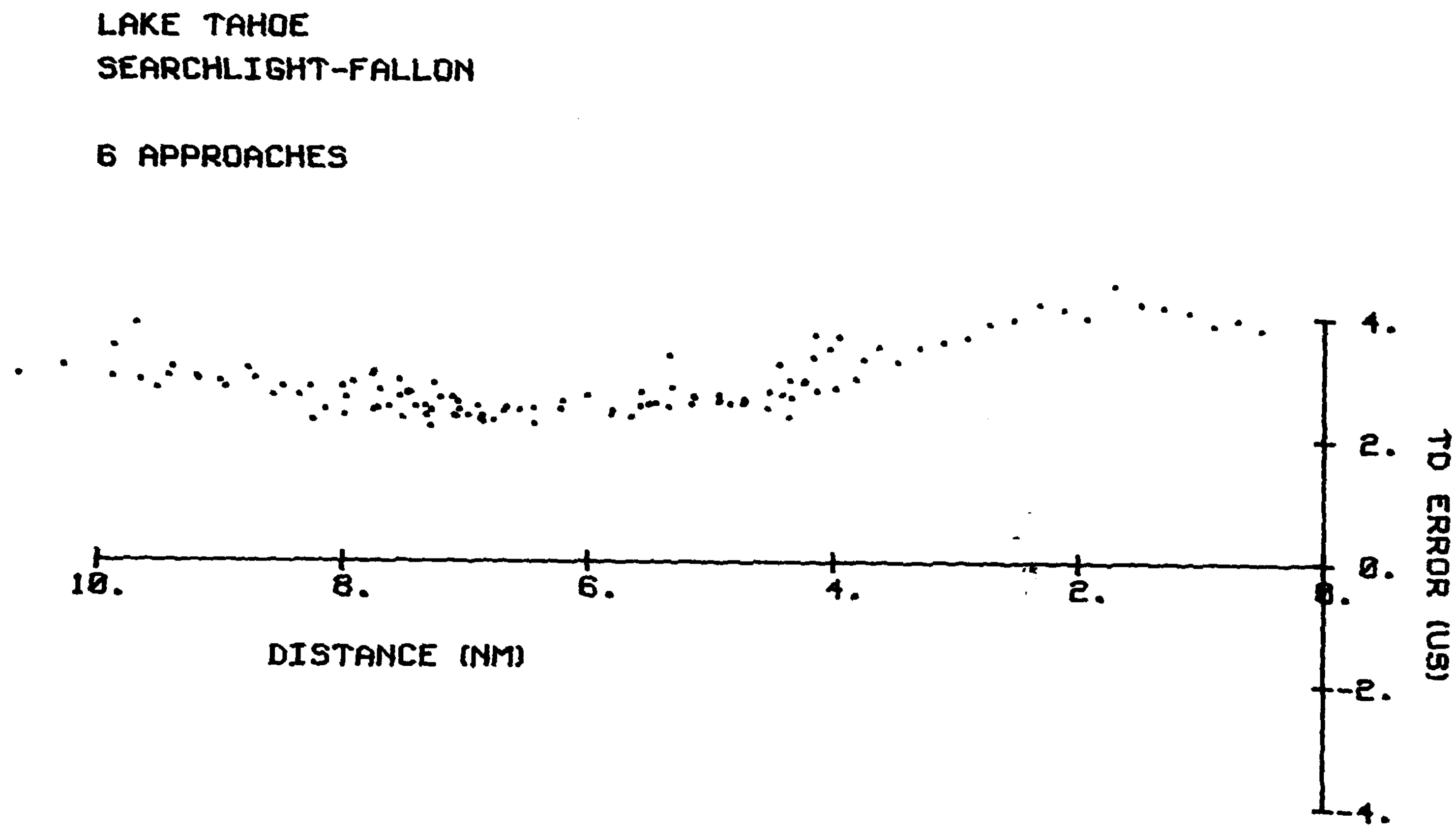
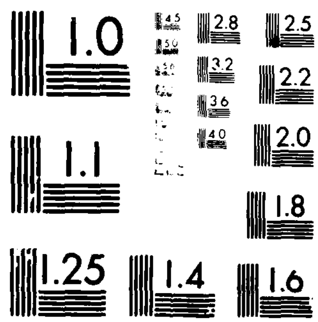


Figure B.3 Time Difference Error at Lake Tahoe for the Searchlight-Fallon Stations

AD-A084 039 SYSTEMS CONTROL INC (VT) PALO ALTO CA F/G 17/7
WEST COAST LORAN-C FLIGHT TEST.(U)
MAR 80 T E SCALISE, E H BOLZ, E D MCCONKEY DOT-FA75WA-3662
UNCLASSIFIED FAA-RD-80-28 NL

3 OF 3
AD
A084 039

END
DATE
FILMED
6-80
DTIC



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963-A

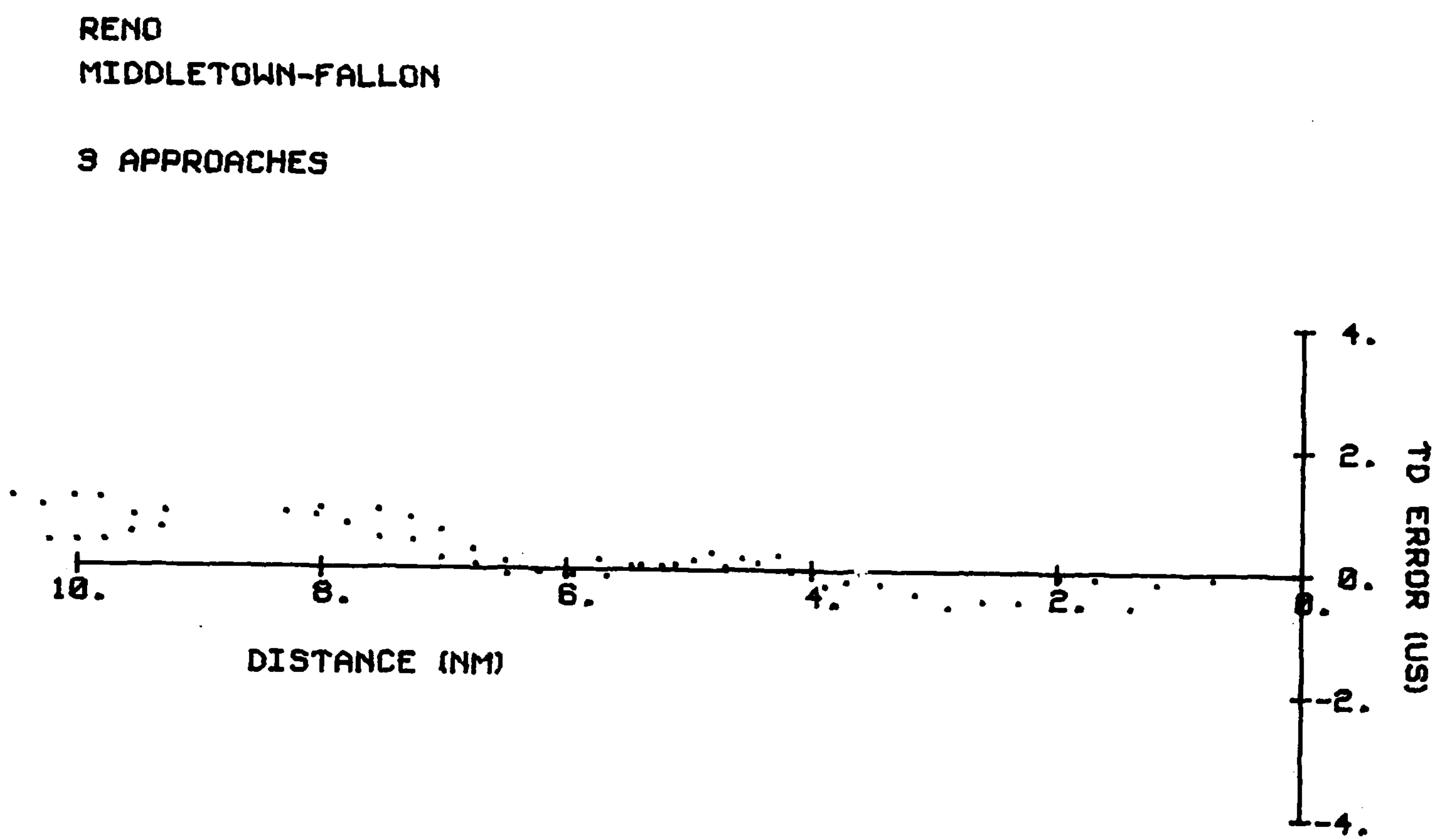


Figure B.4 Time Difference Error at Reno for the Middletown-Fallon Stations

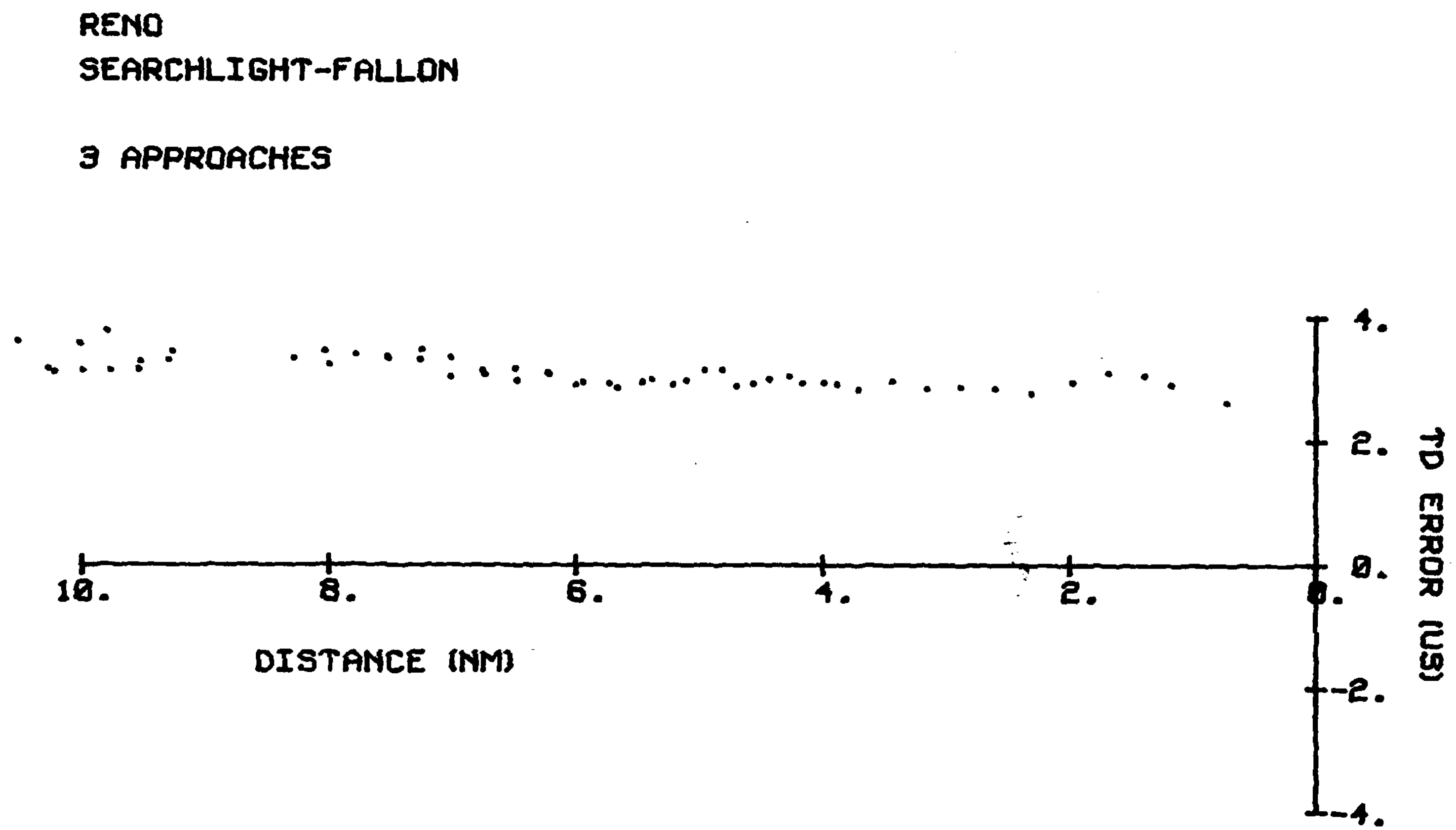


Figure B.5 Time Difference Error at Reno for the Searchlight-Fallon Stations

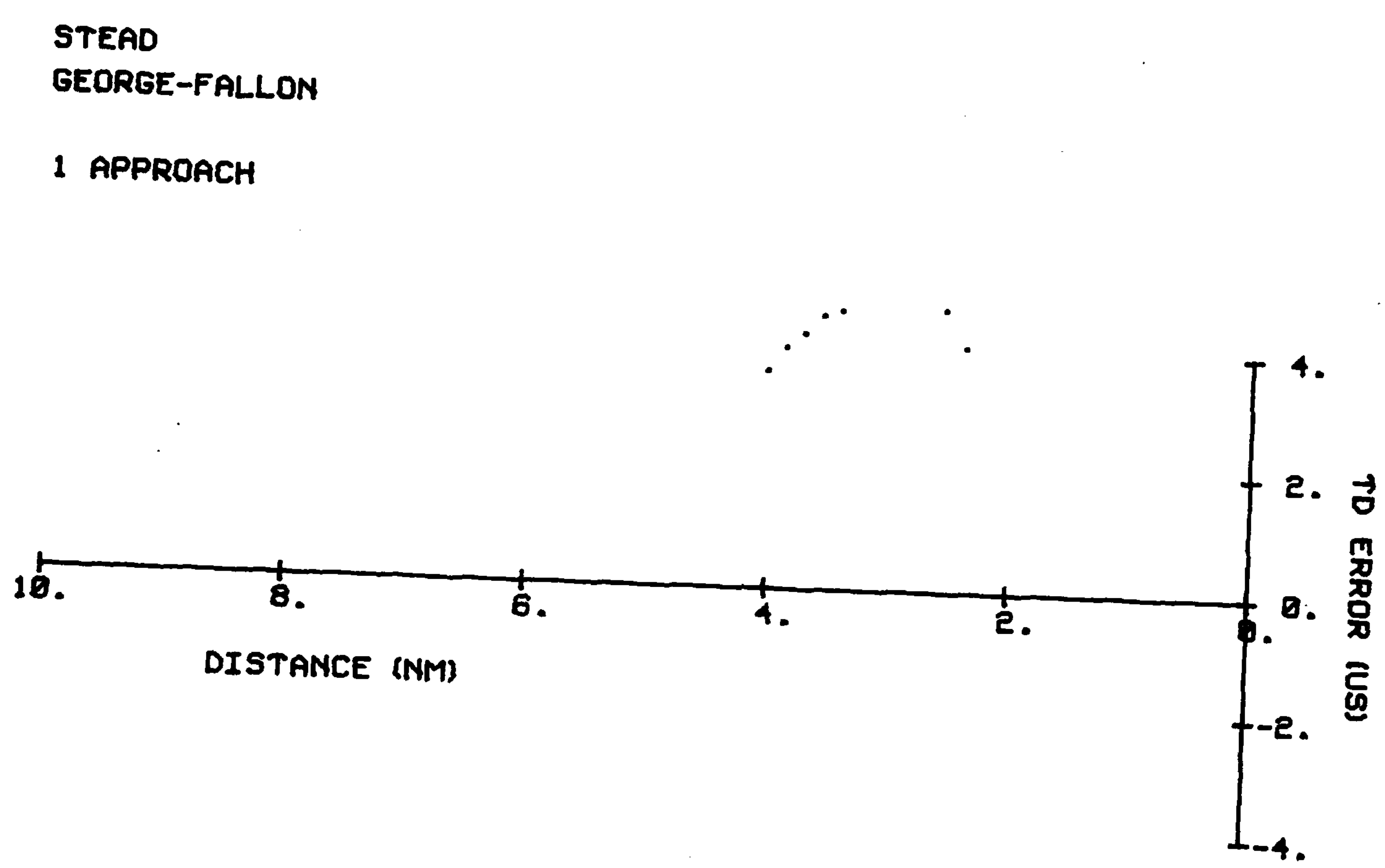


Figure B.6 Time Difference Error at Stead for the George-Fallon Stations

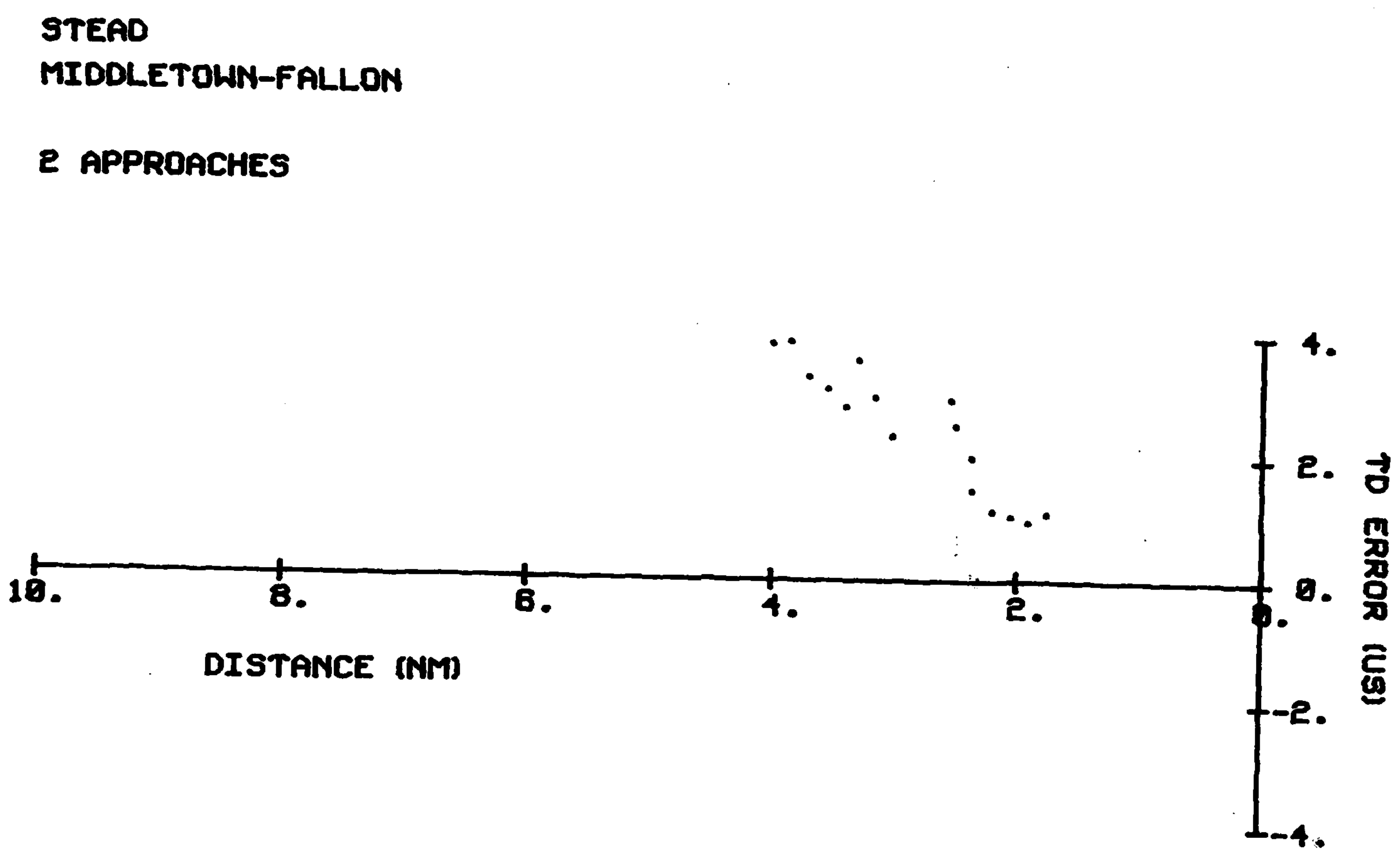


Figure B.7 Time Difference Error at Stead for the Middletown-Fallon Stations

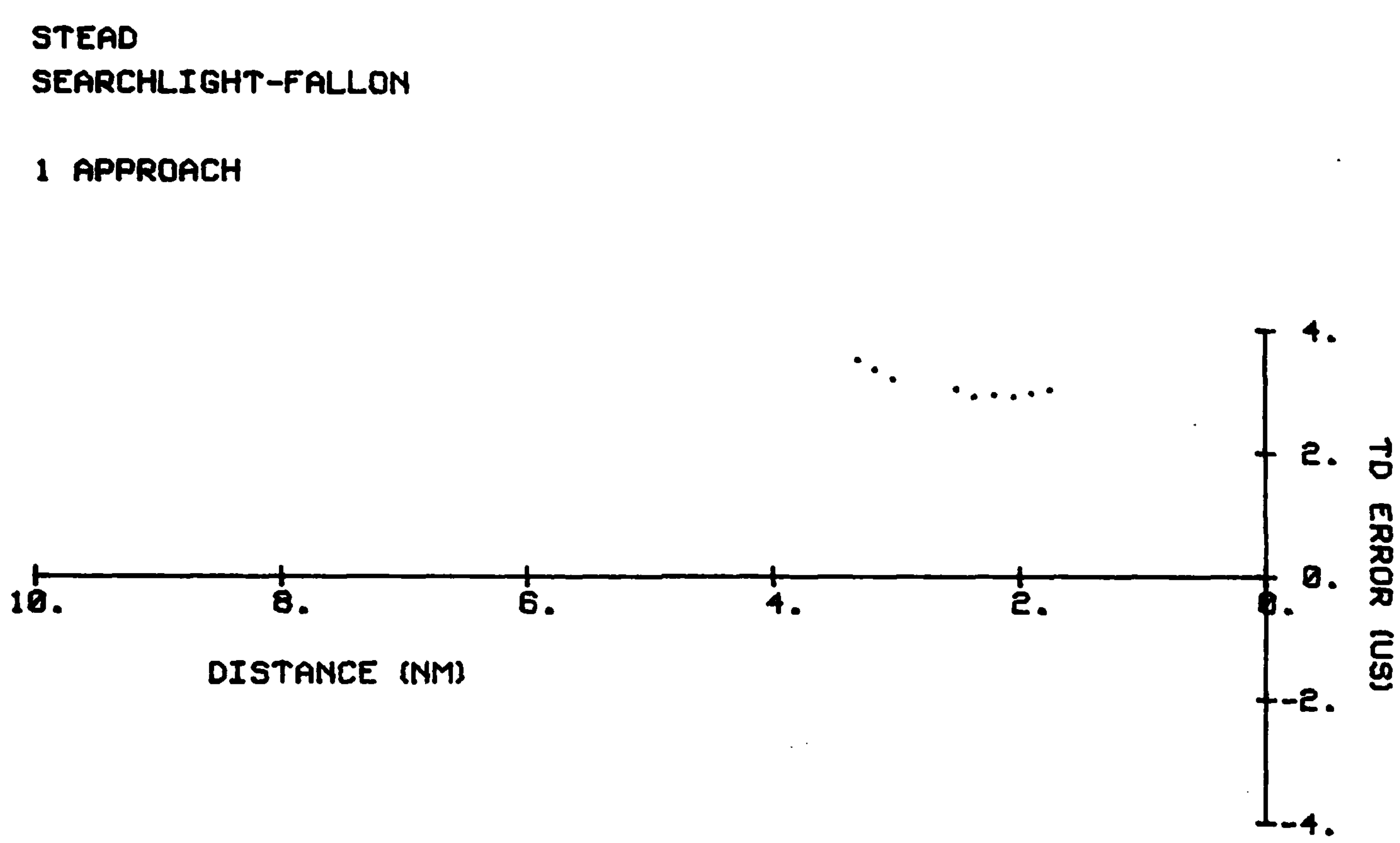


Figure B.8 Time Difference Error at Stead for the Searchlight-Fallon Stations

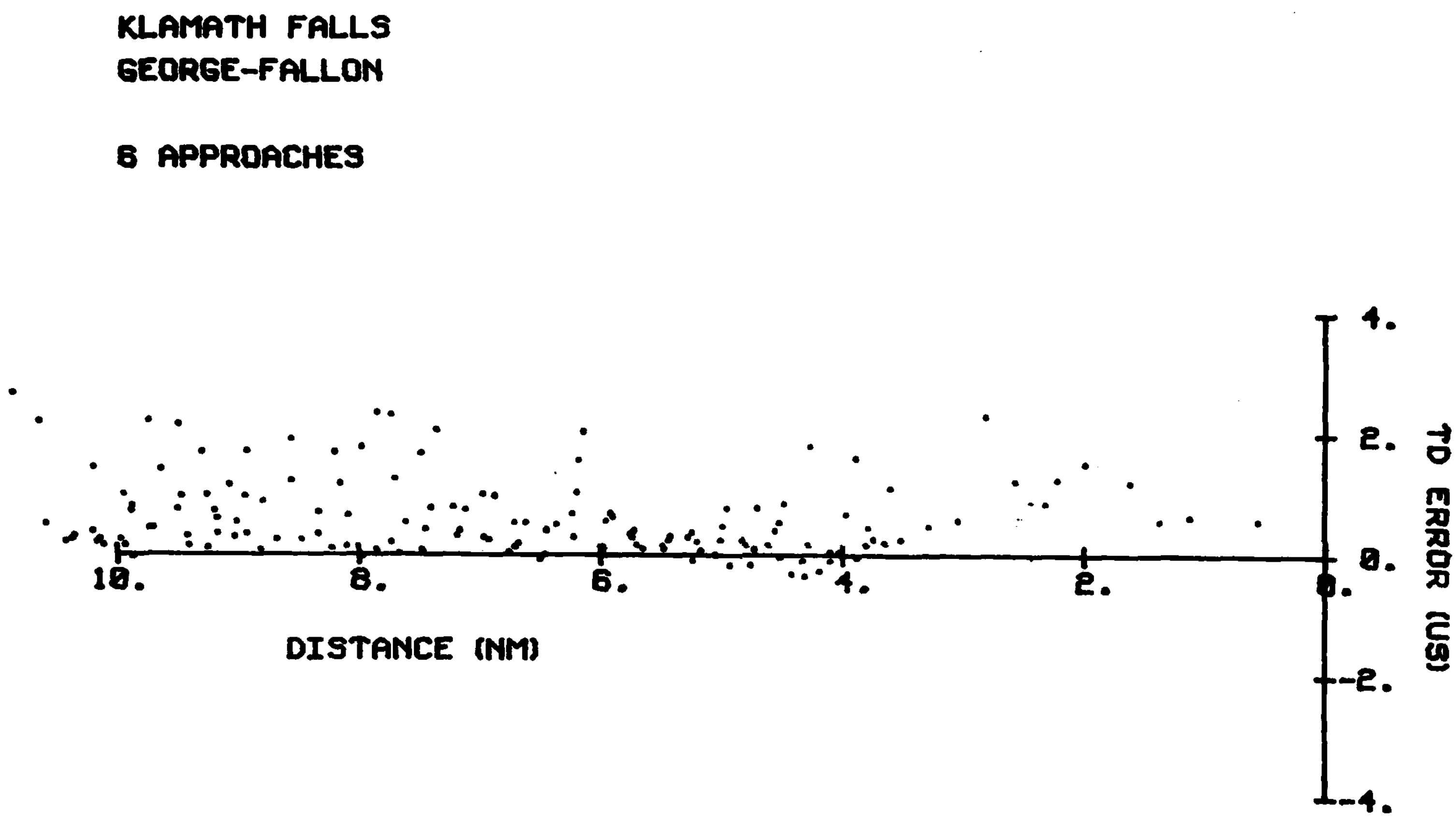


Figure B.9 Time Difference Error at Klamath Falls for the George-Fallon Stations

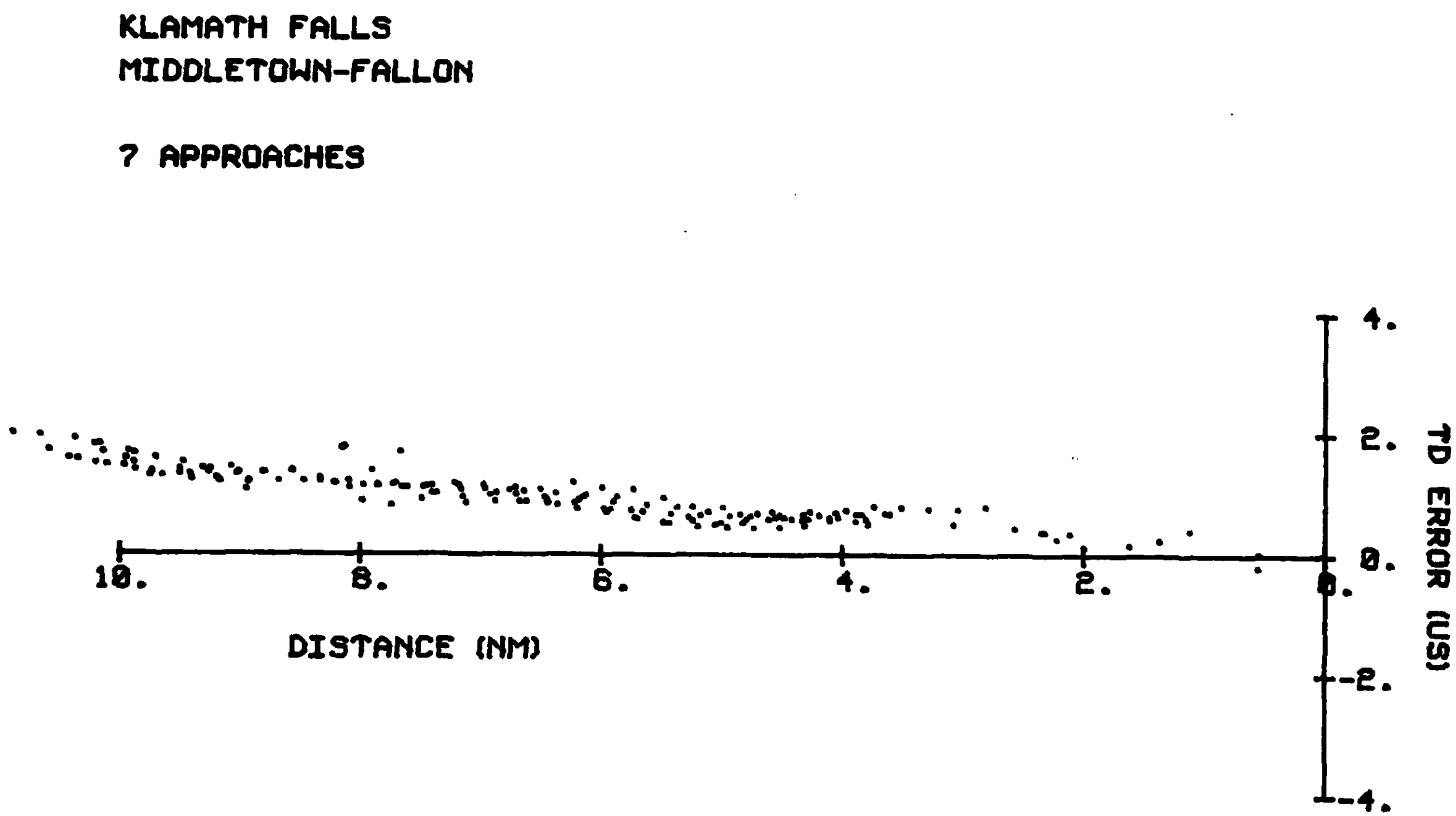


Figure B.10 Time Difference Error at Klamath Falls for the Middletown-Fallon Stations

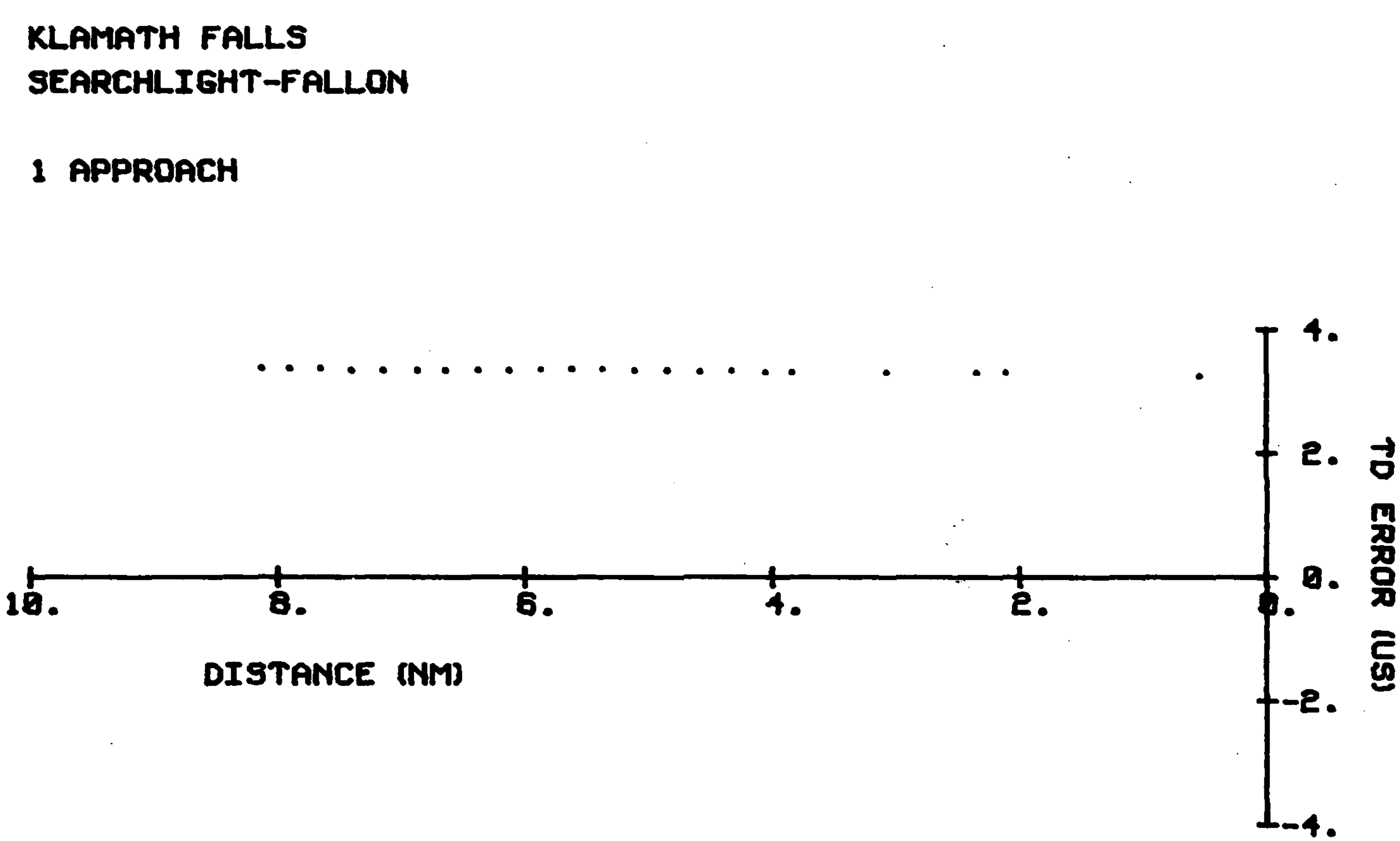


Figure B.11 Time Difference Error at Klamath Falls for the Searchlight-Fallon Stations

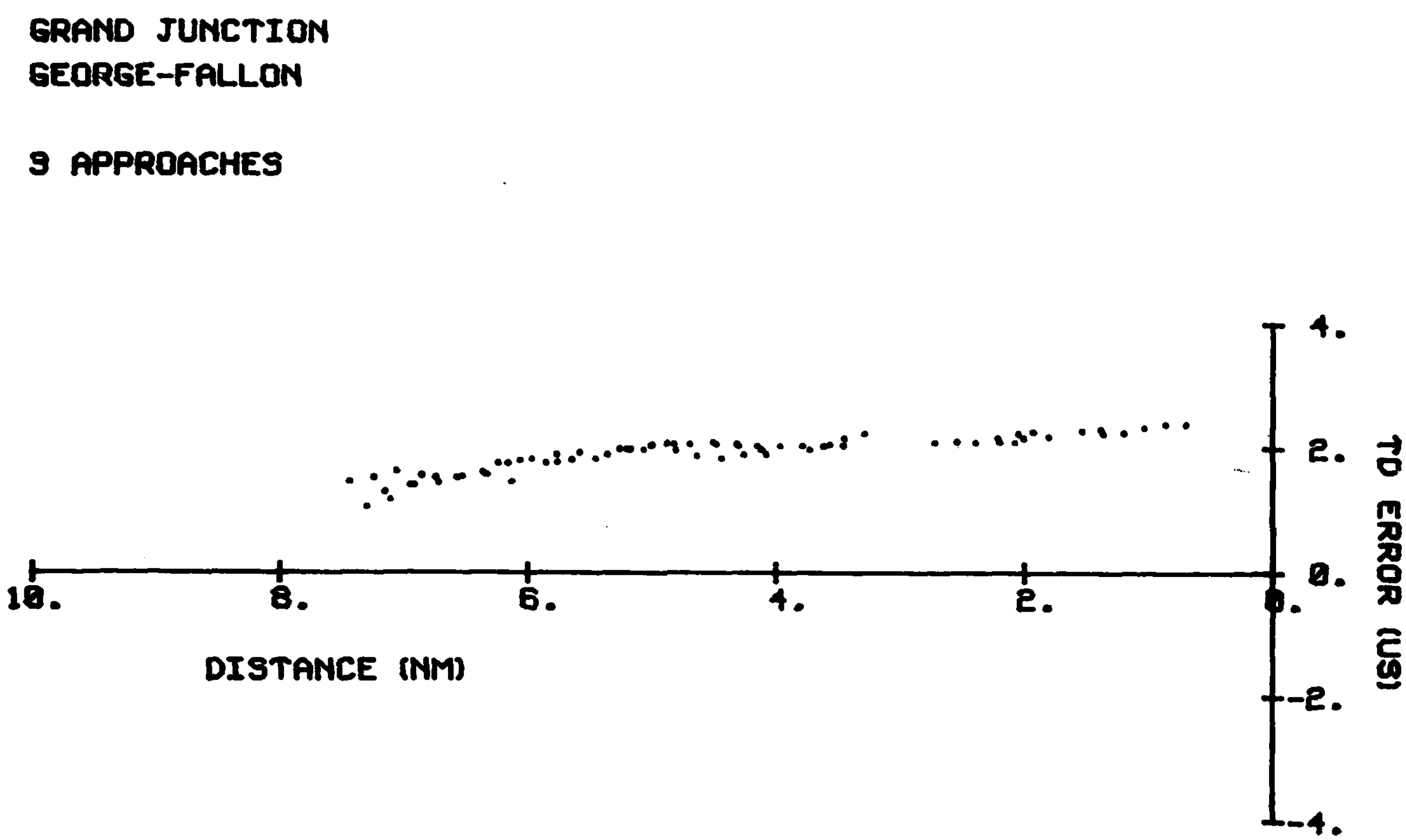


Figure B.12 Time Difference Error at Grand Junction for the George-Fallon Stations

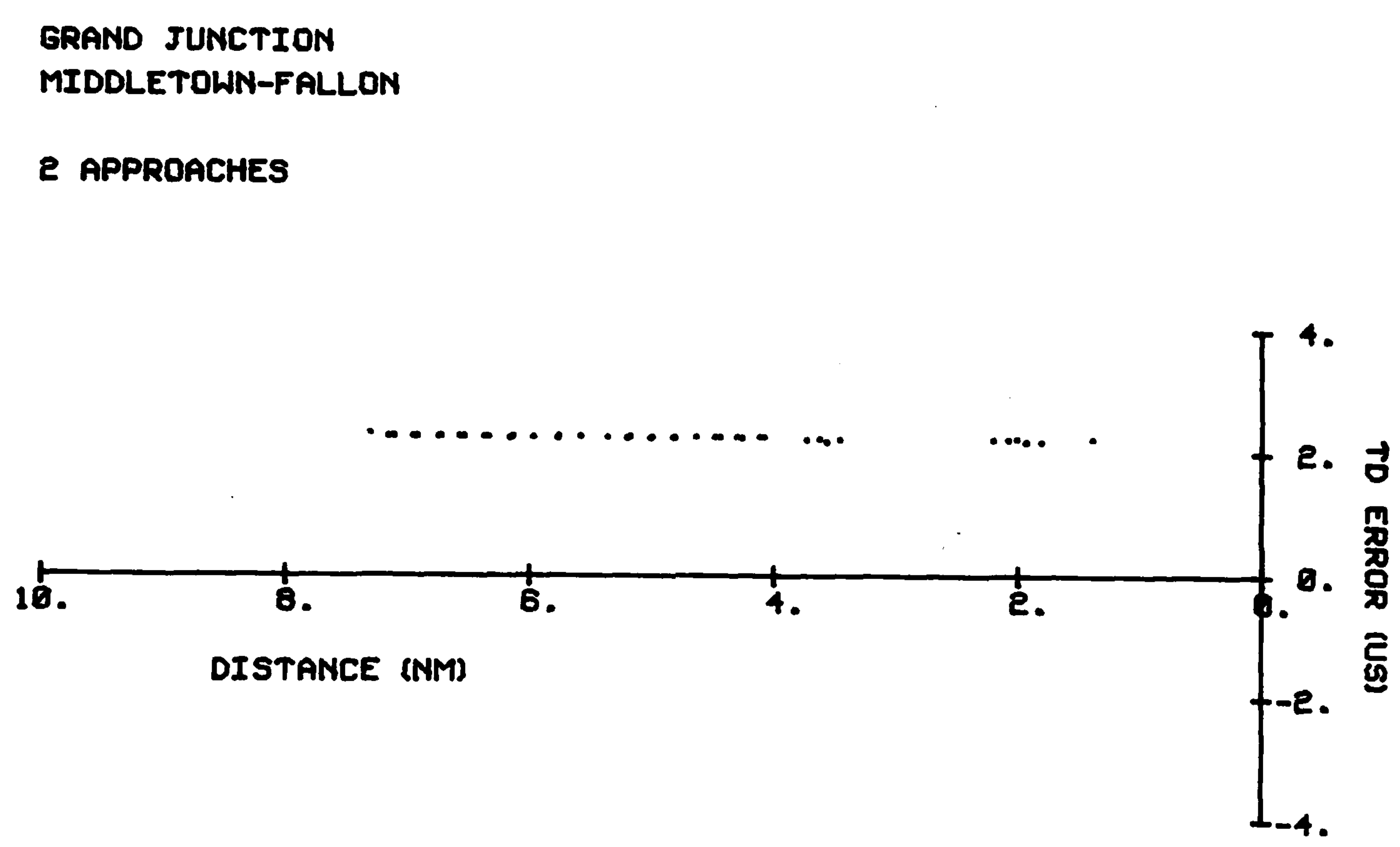


Figure B.13 Time Difference Error at Grand Junction for the Middletown-Fallon Stations

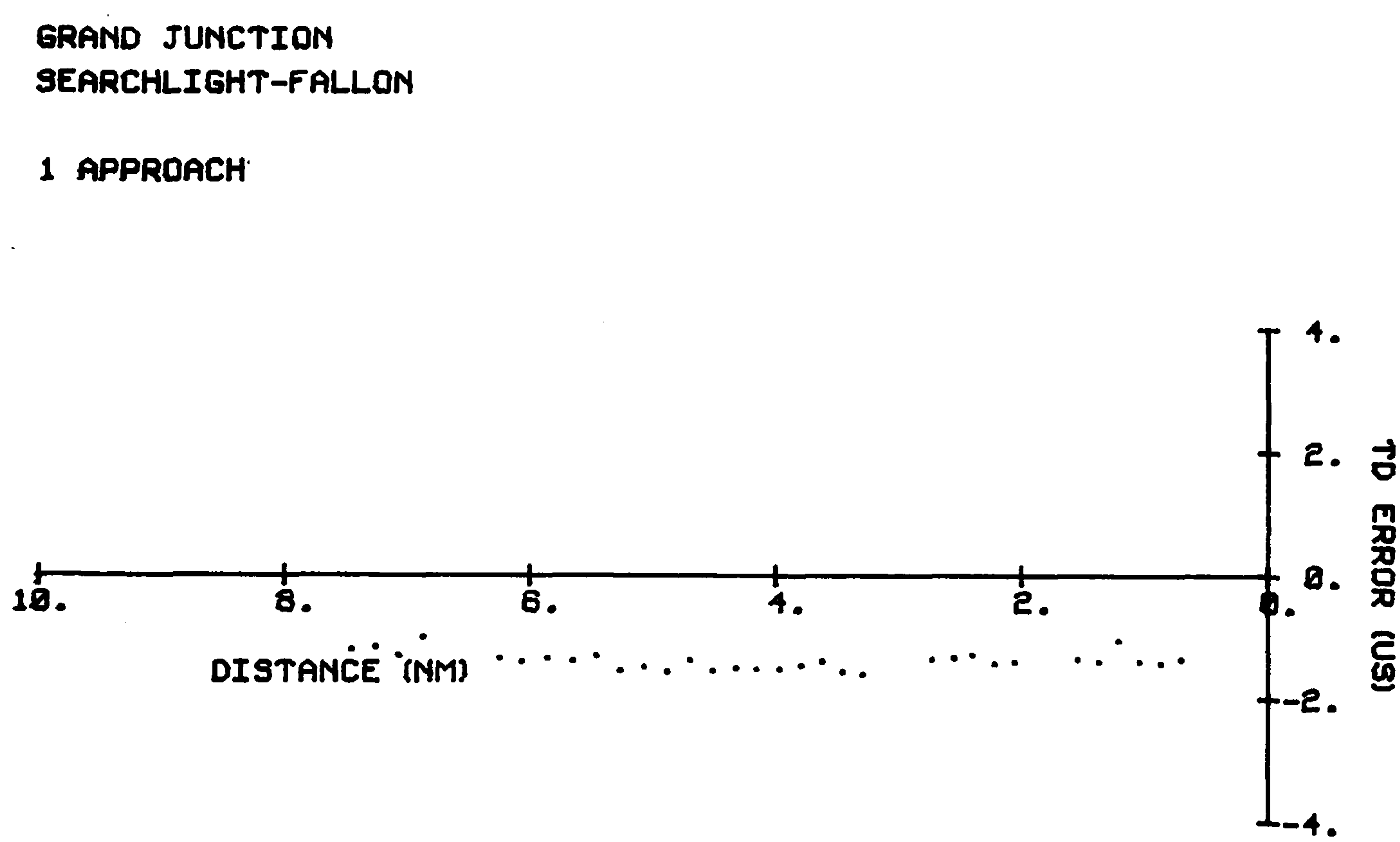


Figure B.14 Time Difference Error at Grand Junction for the Searchlight-Fallon Stations

APPENDIX C

EFFECTS OF TEMPORARY STATION OUTAGE

There were two momentary inflight breaks in lock, both of which occurred on 26 July 1979, during the approaches flown at Lake Tahoe. In Figure C-1, the TDL-711 RDU data stream is represented, beginning at 09:07:05 on the 26th. At about 09:11, the SNR for Station C (Searchlight) dropped from 55 to 12 to 5 and to 0, indicating a loss of that station's signal. At about the same time, the decimal points appeared in the right and left display windows of the Loran-C CDU, indicating a loss of reliable navigation information.

After the station signal was again being received and the Searchlight SNR returned to near normal (which required approximately 30 seconds), almost a minute was required for the navigator to reconverge and produce reliable information. During the reconvergence the cross track deviation (CTD) was unreliable and the CDI navigation flag was in view.

The second occurrence, also the apparent result of a problem with the Searchlight signal, took place at 09:18:12 the same morning (see Figure C-2). Again as the Searchlight SNR's fell, the machine lost track and warned the pilot by illuminating the decimal points. About 30 seconds later the -711 regained track and settled to normal operation again.

Both of the Searchlight incidents have been confirmed as station outages by the U.S. Coast Guard, and the duration of the outages also agreed with the -711 data record. The fact that TDs and lat/lons were not visibly affected indicated that the processor maintained a memory of recent valid time differences. No usable guidance was provided to the pilot, however, since in both cases the decimal points all lit and the nav flag came into view on the Loran-C CDI.

Figures C-3 and C-4 are graphic representations of the station outages. Each graph plots SNR values, cross track deviation, and CDI flagging against actual time. It is interesting to note from these graphs, and from Figures C-1 and C-2, that with the offending station back on the air, an immediate reconvergence was begun and the remainder of the approach was flown without similar interruption.

```
07 26 09 07 5                                          ---- TDL711 RDU DATA ----                                        L072679
                           WFROLH      MTAT                                                       SNR              ENV #                    T
I--LH DISP--I--RH DISP-IFTLFCDDISTSPEDSLRSI--TDA--I--TDB--I----LAT---I---LONG---I CTD TRK M A B C BLK ENV M A B C    OFF      VAR   TRK
------------------------------------------------------------------------------------------------------------------------------------------
          6.0 0 8 0       1     00600128DL2 28444.97 43706.98  39.11.51.-120. 2.55. 5.11MABC55515654     MABC62656359L        E 17    MBCY
          5.7 0 8 0       1     00570125DL2 28448.11 43707.00  39.11.48.-120. 2.33. 4.80MABC56[illegible]5654     MABC63646360L        E 17    MBCY
          5.5 0 8 0       1     00550126DL2 28450.89 43707.07  39.11.46.-120. 2.14. 4.63MABC55505556     MABC63646360L        E 17    MBCY
          5.2 0 7 9       1     00520128DL2 28454.16 43707.21  39.11.44.-120. 1.52. 4.42MABC56525654     MABC63656360L        E 17    MBCY
          4.9 0 7 9       1     00490128DL2 28457.36 43707.33  39.11.42.-120. 1.31. 4.10MABC56515655     MABC62656460L        E 17    MBCY
          4.6 0 8 0       1     00460130DL2 28460.14 43707.46  39.11.41.-120. 1.12. 3.95MABC55495556     MABC62656360L        E 17    MBCY
          4.4 0 8 0       1     00440133DL2 28463.41 43707.64  39.11.40.-120. 0.50. 3.73MABC55515654     MABC63656460L        E 17    MBCY
          4.1 0 8 0       1     00410134DL2 28466.19 43707.83  39.11.39.-120. 0.32. 3.46MABC55535653     MABC63666359L        E 17    MBCY
          3.9 0 8 0       1     00390136DL2 28468.92 43708.00  39.11.38.-120. 0.14. 3.29MABC55515655     MABC63666359L        E 17    MBCY
          3.8 0 8 0       1     00380136DL2 28470.29 43708.09  39.11.38.-120. 0. 5. 3.15MABC55525652     MABC63666359L        E 17    MBCY
          3.4 0 8 1       1     00340138DL2 28475.32 43708.64  39.11.39.-119.59.32. 2.75MABC56535554     MABC63656460L        E 17    MBCY
          3.1 0 8 1       1     00310139DL2 28478.40 43708.95  39.11.39.-119.59.12. 2.55MABC55535655     MABC62646460L        E 17    MBCY
          2.9 0 8 3           L 00290140DL2 28481.33 43709.28  39.11.40.-119.58.53. 2.36MABC56505654     MABC63646460L        E 17    MBCY
          2.8 0 8 3      12   L 00280140DL2 28482.36 43709.37  39.11.40.-119.58.46. 2.25MABC56515655     MABC63646461L        E 17    MBCY
          7.5 1 5 2      12     00750141DL2 28487.07 43709.78  39.11.39.-119.58.15. 2.30MABC56505656     MABC64646461L        E 17    MBCY
          7.4 1 5 2      12     00740141DL2 28489.02 43709.72  39.11.37.-119.58. 1. 2.07MABC55525654     MABC63646461L        E 17    MBCY
          7.3 1 5 6      12     00730142DL2 28491.31 43709.25  39.11.30.-119.57.44. 1.93MABC55495654     MABC63646361L        E 17    MBCY
          7.2 1 5 6      12     00720141DL2 28492.84 43708.55  39.11.22.-119.57.31. 1.69MABC555[illegible]5654     MABC63646460L        E 17    MBCY
          7.1 1 5 8      12     00710140DL2 28494.06 43707.38  39.11.10.-119.57.18. 1.55MABC56525555     MABC62636460L        E 17    MBCY
          6.9 1 6 0      12     00690137DL2 28494.79 43705.80  39.10.54.-119.57. 7. 1.40MABC56505655     MABC63636360L        E 17    MBCY
          6.7 1 6 1      12     00670135DL2 28494.80 43704.46  39.10.41.-119.57. 1. 1.34MABC55525454     MABC64626359L        E 17    MBCY
          6.5 1 6 1      12     00650129DL2 28494.27 43702.72  39.10.25.-119.56.58. 1.24MABC56525555     MABC64606358L        E 17    MBCY
          5.9 1 6 2      12     00590127DL2 28493.69 43701.18  39.10.11.-119.56.57. 1.20MABC55525652     MABC64616558L        E 17    MBCY
          5.7 1 6 2      12     00570125DL2 28492.96 43699.36  39. 9.54.-119.56.55. 1.13MABC55505652     MABC63626559L        E 17    MBCY
          5.4 1 6 2      12     00540122DL2 28492.28 43697.61  39. 9.38.-119.56.53. 1.05MABC56525654     MABC63626559L        E 17    MBCY
          5.2 1 6 2      12     00520123DL2 28491.75 43696.19  39. 9.25.-119.56.51.  .99MABC56525655     MABC63626460L        E 17    MBCY
          5.0 1 6 2      12     00500122DL2 28491.23 43694.98  39. 9.14.-119.56.50.  .94MABC56525654     MABC64626461L        E 17    MBCY
          4.7 1 6 3      12     00470123DL2 28490.20 43692.97  39. 8.56.-119.56.50.  .89MABC56515654     MABC63626360L        E 17    MBCY
          4.4 1 6 3      12     00440124DL2 28489.43 43691.26  39. 8.41.-119.56.49.  .83MABC55495655     MABC63626360L        E 17    MBCY
          4.2 1 6 3      12     00420126DL2 28488.88 43689.50  39. 8.25.-119.56.46.  .74MABC55505512     MABC63626359L        E 17    MBCY
          3.9 1 6 3      12     00390127DL2 28488.56 43687.99  39. 8.11.-119.56.42.  .64MABC55505605     MABC63616358L        E 17    MBCY
  . . . .3.7 1.6.4. . .  12     00370129DL2 28488.25 43686.42  39. 7.57.-119.56.39.  .55MAB 52525600     MABC63606458L        E 17    MBCN
  . . . .3.6 1.6.4. . .  12     00360129DL2 28488.16 43685.94  39. 7.52.-119.56.37.  .51MAB 54515500     MABC63616258L        E 17    MBCN
  . . . .3.6 1.6.4. . .  12     00360129DL2 28488.16 43685.94  39. 7.52.-119.56.37.  .51MAB 54515500     MABC63616258L        E 17    MBCN
  . . . . .   . . . . .  12     11560020DL2 28487.12 43682.01  37. 0.12.-119.22.15.-9.00MABC55525652     MABC63626459L        E 17    MBCY
  . . . . .   . . . . .  12     11560006DL2 28486.66 43681.25  37. 0.13.-119.22.20.-9.00MABC55525655     MABC63626559L        E 17    MBCY
  . . . . .   . . . . .  12     00280008DL2 28485.96 43680.19  39. 7. 1.-119.56.31.  .15MABC55505655     MABC63626559L        E 17    MBCY
  . . . . .   . . . . .  12     54540018DL2 28484.85 43678.68  40.14.47.-131.37.55.99.00MABC56515551     MABC62626460L        E 17    MBCY
N .4.0.1.4.5W1.3.1.3.8.012      54550030FL2 28483.55 43676.94  40.14.33.-131.38. 4.99.00MABC55525654     MABC63616360L        E 17    MBCY
N .4.0.1.4.3W1.3.1.3.8.112      54560040FL2 28482.36 43675.34  40.14.20.-131.38.11.99.00MABC56485654     MABC63626360L        E 17    MBCY
N .4.0.1.4.0W1.3.1.3.8.312      54570052FL2 28480.97 43673.49  40.14. 5.-131.38.20.99.00MABC56515654     MABC63626461L        E 17    MBCY
N .9.5.5.8.1E . .0.2.2.612      97790080FL2 28479.54 43671.61  95.58. 8.   0.22.41.-9.00MABC56535654     MABC62616461L        E 17    MBCY
N .3.8.4.0.9W1.2.0.0.4.512      07050888FL2 28478.25 43669.92  38.40.57.-120. 4.33.-7.17MABC56495655     MABC62636462L        E 17    MBCY
N .3.8.4.0.7W1.2.0.0.4.612      07080351FL2 28476.81 43668.01  38.40.43.-120. 4.39.-7.12MABC56515655     MABC61636363L        E 17    MBCY
N .3.9.0.4.3W1.1.9.5.5.912      02330168FL2 28475.66 43666.47  39. 4.20.-119.55.58.-5.02MABC55515656     MABC62636563L        E 17    MBCY
N .3.9.0.4.8W1.1.9.5.6.812      00060104FL2 28474.34 43664.68  39. 4.49.-119.56.53.  .03MABC55525555     MABC63636563L        E 17    MBCY
N  3 9.0 4.5W1 1 9.5 6.912      00030082FL2 28472.99 43662.82  39. 4.34.-119.56.55.  .02MABC56505655     MABC63636464L        E 17    MBCY
          0.1 1 6 2      12     00010105DL2 28471.77 43661.12  39. 4.20.-119.56.57.  .14MABC55505654     MABC63636464L        E 17    MBCY
          0.0 1 3 7           L 00000111DL2 28470.47 43659.34  39. 4. 4.-119.56.60.  .12MABC56535652     MABC63646464L        E 17    MBCY
          0.2 1 3 7      23   L 00020116DL2 28469.27 43657.59  39. 3.50.-119.57. 1.  .10MABC55525654     MABC62646464L        E 17    MBCY
  2.3.B.8.0.0 4.3.0.1.2.03E 0     23B7  OL1 41320.44107365.67 156.45.28. 211.52.37.99.00M     00646496MABCMABC00634300R  0001W037   MBCY
          4.0 1 7 3      23     00400125DL2 28466.73 43653.62  39. 3.17.-119.57. 4. -.03MABC56525653     MABC63636364L        E 17    MBCY
          3.8 1 7 5      23     00380128DL2 28465.54 43651.91  39. 3. 2.-119.57. 6.  .10MABC55505654     MABC63636364L        E 17    MBCY
          3.5 1 7 5      23     00350131DL2 28464.05 43650.00  39. 2.47.-119.57. 9. -.01MABC55505654     MABC64646464L        E 17    MBCY
          3.3 1 7 5      23     00330133DL2 28462.78 43648.36  39. 2.33.-119.57.12. -.01MABC55495654     MABC62646463L        E 17    MBCY
          3.1 1 7 6      23     00310135DL2 28461.55 43646.71  39. 2.19.-119.57.14. -.03MABC56525653     MABC61646364L        E 17    MBCY
          2.8 1 7 6      23     00280137DL2 28459.87 43644.48  39. 2. 1.-119.57.17.  .06MABC55525655     MABC62646463L        E 17    MBCY
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Figure C-1   TDL-711 RDU Data (26 July 1979)

```
07 26 09 13 35                                          -- - TDL711 RDU DATA  --                                              L072679
                          WPROLH         MTAT                                                           CNR              ENV #                T
I--LH DISP--I--RH DISP-IFTLFCDDISTSPEDSLRSI--TDA--I--TDB--I----LAT---I---LONG---I CTD TRK M A B C BLI ENV M A B C    OFF    VAR  TRK
-------------------------------------------------------------------------------------------------------------------------------------
          2.5 1 7 7     23     00250139DL2 28458.59 43642.80  39. 1.47.-119.57.20. -.07MABC54515653   MABC62646562L        E 17  MBCY
          2.3 1 7 7     23     00230140DL2 28457.07 43640.90  39. 1.31.-119.57.23. -.07MABC55525654   MABC62656561L        E 17  MBCY
          2.0 1 7 8     23     00200141DL2 28455.78 43639.33  39. 1.19.-119.57.26. -.08MABC56515655   MABC61676561L        E 17  MBCY
          1.8 1 7 9     23     00180141DL2 28454.32 43637.53  39. 1. 4.-119.57.30. -.10MABC55495656   MABC61676461L        E 17  MBCY
          1.6 1 7 9     23     00160141DL2 28452.78 43635.74  39. 0.49.-119.57.34. -.08MABC56515555   MABC62666360L        E 17  MBCY
          1.3 1 8 0     23     00130141DL2 28451.46 43634.23  39. 0.37.-119.57.37. -.08MABC56535656   MABC62656361L        E 17  MBCY
          1.1 1 8 1     34   L 00110140DL2 28449.77 43632.51  39. 0.23.-119.57.43. -.07MABC55505655   MABC62666362L        E 17  MBCY
          1.0 1 8 1     34   L 00100140DL2 28448.66 43631.45  39. 0.15.-119.57.46. -.04MABC55515554   MABC61666461L        E 17  MBCY
          5.6 1 7 6     34     00560138DL2 28446.95 43629.89  39. 0. 2.-119.57.53. -.04MABC56525655   MABC62666362L        E 17  MBCY
          5.4 1 7 5     34     00540137DL2 28444.97 43628.07  38.59.47.-119.57.60.  .09MABC56535655   MABC62676563L        E 17  MBCY
          5.2 1 7 5     34     00520136DL2 28443.52 43626.63  38.59.36.-119.58. 4.  .13MABC55515555   MABC62666462L        E 17  MBCY
          4.9 1 7 5     34     00490135DL2 28442.00 43624.92  38.59.22.-119.58. 8.  .05MABC55515656   MABC64676562L        E 17  MBCY
          4.7 1 7 5     34     00470135DL2 28440.82 43623.46  38.59.10.-119.58.11.  .04MABC55535654   MABC63676563L        E 17  MBCY
          4.5 1 7 5     34     00450135DL2 28439.46 43621.72  38.58.56.-119.58.14.  .04MABC56525655   MABC64666464L        E 17  MBCY
          4.3 1 7 5     34     00430134DL2 28438.14 43620.06  38.58.43.-119.58.17.  .03MABC55485654   MABC64646563L        E 17  MBCY
          4.1 1 7 5     34     00410134DL2 28437.11 43618.68  38.58.31.-119.58.19.  .01MABC56515655   MABC63646564L        E 17  MBCY
          3.9 1 7 5     34     00390132DL2 28436.00 43617.16  38.58.19.-119.58.21. -.00MABC56515655   MABC62646564L        E 17  MBCY
          3.7 1 7 5     34     00370131DL2 28435.14 43615.92  38.58. 9.-119.58.23. -.03MABC55505654   MABC62656464L        E 17  MBCY
          3.5 1 7 6     34     00350129DL2 28434.23 43614.50  38.57.58.-119.58.24. -.06MABC56515655   MABC62646564L        E 17  MBCY
          3.3 1 7 6     34     00330126DL2 28433.37 43613.11  38.57.46.-119.58.25. -.09MABC55515655   MABC60656665L        E 17  MBCY
          3.2 1 7 7     34     00320124DL2 28432.66 43611.92  38.57.37.-119.58.25. -.12MABC55525655   MABC61656765L        E 17  MBCY
          3.0 1 7 8     34     00300122DL2 28431.69 43610.57  38.57.26.-119.58.27. -.13MABC55515655   MABC62646665L        E 17  MBCY
          2.8 1 7 8     34     00280120DL2 28430.74 43609.39  38.57.16.-119.58.29. -.13MABC56515655   MABC63636765L        E 17  MBCY
          2.7 1 7 8     34     00270118DL2 28429.57 43608.02  38.57. 5.-119.58.32. -.13MABC56515655   MABC63646764L        E 17  MBCY
          2.5 1 7 9     34     00250117DL2 28428.28 43606.68  38.56.55.-119.58.36. -.11MABC56495656   MABC64646865L        E 17  MBCY
          2.3 1 7 9     34     00230115DL2 28426.91 43605.62  38.56.46.-119.58.42. -.05MABC55495655   MABC63646865L        E 17  MBCY
          2.2 1 7 8      1   L 00220113DL2 28424.97 43604.75  38.56.40.-119.58.52.  .06MABC56525556   MABC63636765L        E 17  MBCY
        1 4.7 3 5 3      1     01470108DL2 28423.17 43604.46  38.56.38.-119.59. 4. -.36MABC55475656   MABC62646665L        E 17  MBCY
        1 4.7 3 5 3      1     01470100DL2 28421.30 43604.70  38.56.40.-119.59.17. -.59MABC55515655   MABC64656765L        E 17  MBCY
        1 4.5 3 5 5      1     01450091DL2 28419.95 43605.56  38.56.47.-119.59.30. -.73MABC55525655   MABC64666764L        E 17  MBCY
        1 4.3 3 5 5      1     01430078DL2 28419.24 43606.74  38.56.57.-119.59.39. -.91MABC55515655   MABC63666763L        E 17  MBCY
        1 4.5 3 5 6      1     01450067DL2 28418.63 43608.19  38.57. 9.-119.59.49. -.97MABC56525554   MABC63666763L        E 17  MBCY
        1 4.5 3 5 6      1     01450060DL2 28418.26 43609.59  38.57.21.-119.59.57.-1.05MABC56515655   MABC62656765L        E 17  MBCY
        1 4.4 3 5 6      1     01440055DL2 28418.09 43610.28  38.57.26.-120. 0. 0.-1.13MABC56515655   MABC63656765L        E 17  MBCY
        1 4.2 3 5 7      1     01420054DL2 28417.77 43612.14  38.57.42.-120. 0. 9.-1.26MABC55535655   MABC61666765L        E 17  MBCY
        1 4.0 3 5 8      1     01400057DL2 28417.48 43613.90  38.57.57.-120. 0.18.-1.41MABC55515655   MABC62666664L        E 17  MBCY
        1 3.8 3 5 8      1     01380057DL2 28417.19 43615.58  38.58.11.-120. 0.26.-1.58MABC55505655   MABC62656664L        E 17  MBCY
        1 3.7 3 5 9      1     01370064DL2 28417.08 43616.43  38.58.18.-120. 0.30.-1.63MABC55515655   MABC63646564L        E 17  MBCY
        1 3.5 3 5 9      1     01350067DL2 28416.93 43618.13  38.58.32.-120. 0.37.-1.79MABC55515655   MABC64646564L        E 17  MBCY
        1 3.3 0 0 0      1     01330075DL2 28416.87 43619.63  38.58.45.-120. 0.43.-1.89MABC56525554   MABC63636563L        E 17  MBCY
        1 3.1 0 0 1      1     01310081DL2 28416.92 43621.15  38.58.58.-120. 0.48.-1.98MABC56525655   MABC63636663L        E 17  MBCY
        1 3.0 0 0 1      1     01300084DL2 28416.99 43622.59  38.59.10.-120. 0.53.-2.09MABC56515655   MABC63636663L        E 17  MBCY
        1 2.9 0 0 2      1     01290087DL2 28417.08 43623.43  38.59.17.-120. 0.55.-2.12MABC55505555   MABC62636663L        E 17  MBCY
        1 2.7 0 0 2      1     01270091DL2 28417.25 43625.28  38.59.33.-120. 1. 1.-2.26MABC56525655   MABC62636663L        E 17  MBCY
        1 2.5 0 0 3      1     01250094DL2 28417.38 43626.53  38.59.44.-120. 1. 5.-2.33MABC55515654   MABC61636663L        E 17  MBCY
        1 2.4 0 0 3      1     01240096DL2 28417.50 43627.36  38.59.51.-120. 1. 7.-2.38MABC55515555   MABC61646663L        E 17  MBCY
        1 2.4 0 0 3      1     01240096DL2 28417.50 43627.36  38.59.51.-120. 1. 7.-2.38MABC55515555   MABC61646663L        E 17  MBCY
        1 2.0 0 0 5      1     01200102DL2 28418.09 43630.62  39. 0.19.-120. 1.15.-2.55MABC56525611   MABC62636564L        E 17  MBCY
. . .1.1.8 0.0.5. . .    1     01180105DL2 28418.53 43632.18  39. 0.32.-120. 1.18.-2.64MAB 55505602   MABC62636564L        E 17  MBCN
. . .1.1.8 0.0.5. . .    1     01180105DL2 28418.53 43632.18  39. 0.32.-120. 1.18.-2.64MAB 55505602   MABC62636564L        E 17  MBCN
. . . . .    . . . . .   1     00990027DL2 16390.23 28419.63  39.24.60.-121. 8.57.-9.00MABC55515506   MABC62646564L        E 17  MABY
. . . . .    . . . . .   1     00990027DL2 16390.23 28419.63  39.24.60.-121. 8.57.-9.00MABC55515506   MABC62646564L        E 17  MABY
. . . . .    . . . . .   1     11350005DL2 28420.62 43636.72  36.58. 5.-119.24.40.55.12MABC55515654   MABC62646464L        E 17  MBCY
. . . . .    . . . . .   1     11350005DL2 28420.62 43636.72  36.58. 5.-119.24.40.55.12MABC55515654   MABC62646464L        E 17  MBCY
. . . . .    . . . . .   1     11350005DL2 28420.62 43636.72  36.58. 5.-119.24.40.55.12MABC55515654   MABC62646464L        E 17  MBCY
          .              1     01080025DL2 28421.59 43639.96  39. 1.38.-120. 1.25.-2.93MABC56505655   MABC63646464L        E 17  MBCY
          .              1     01080025DL2 28421.59 43639.96  39. 1.38.-120. 1.25.-2.93MABC56505655   MABC63646464L        E 17  MBCY
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Figure C-2   TDL-711 RDU Data (26 July 1979)

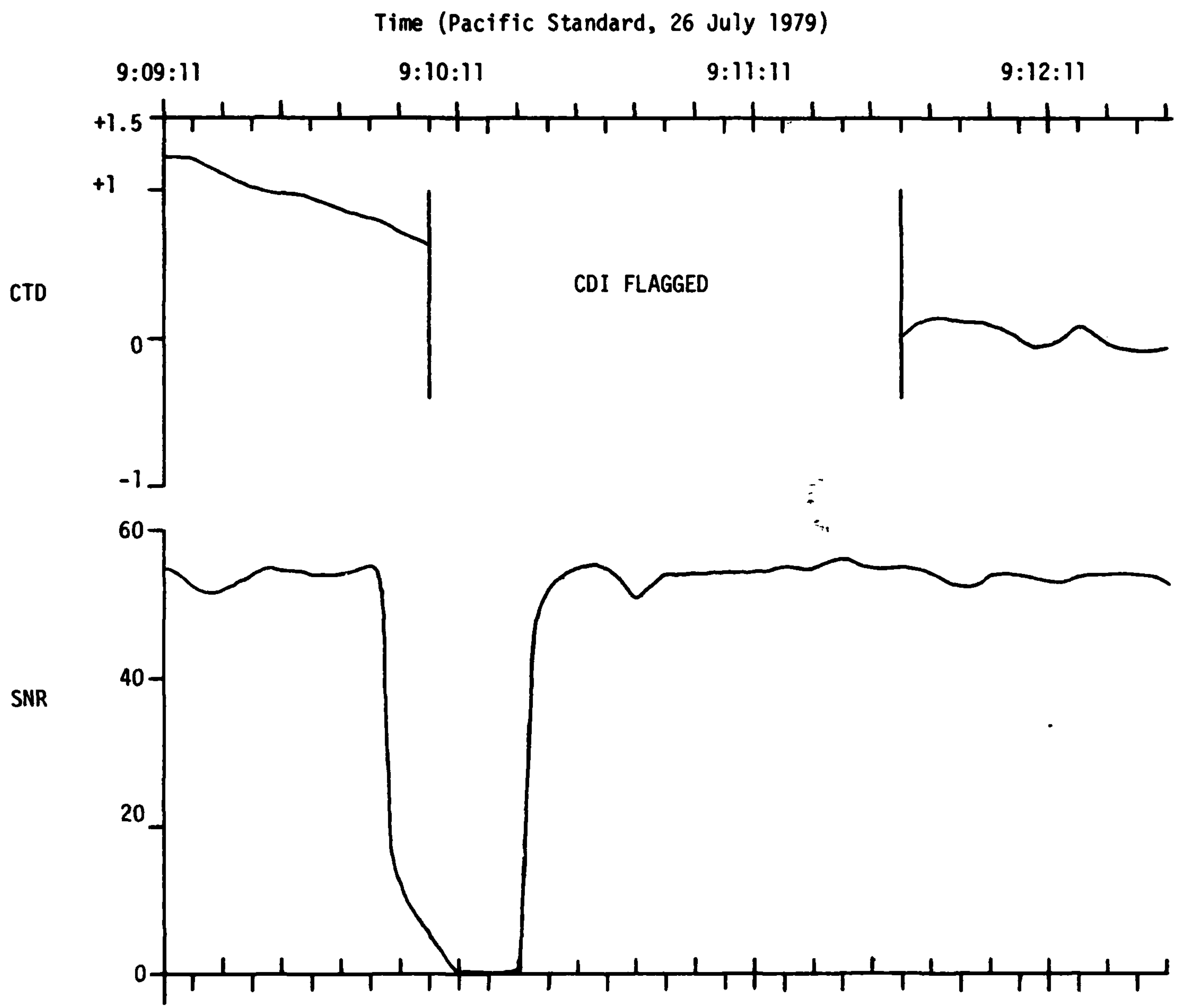

Figure C.3 Effects of Momentary Searchlight Station Outage

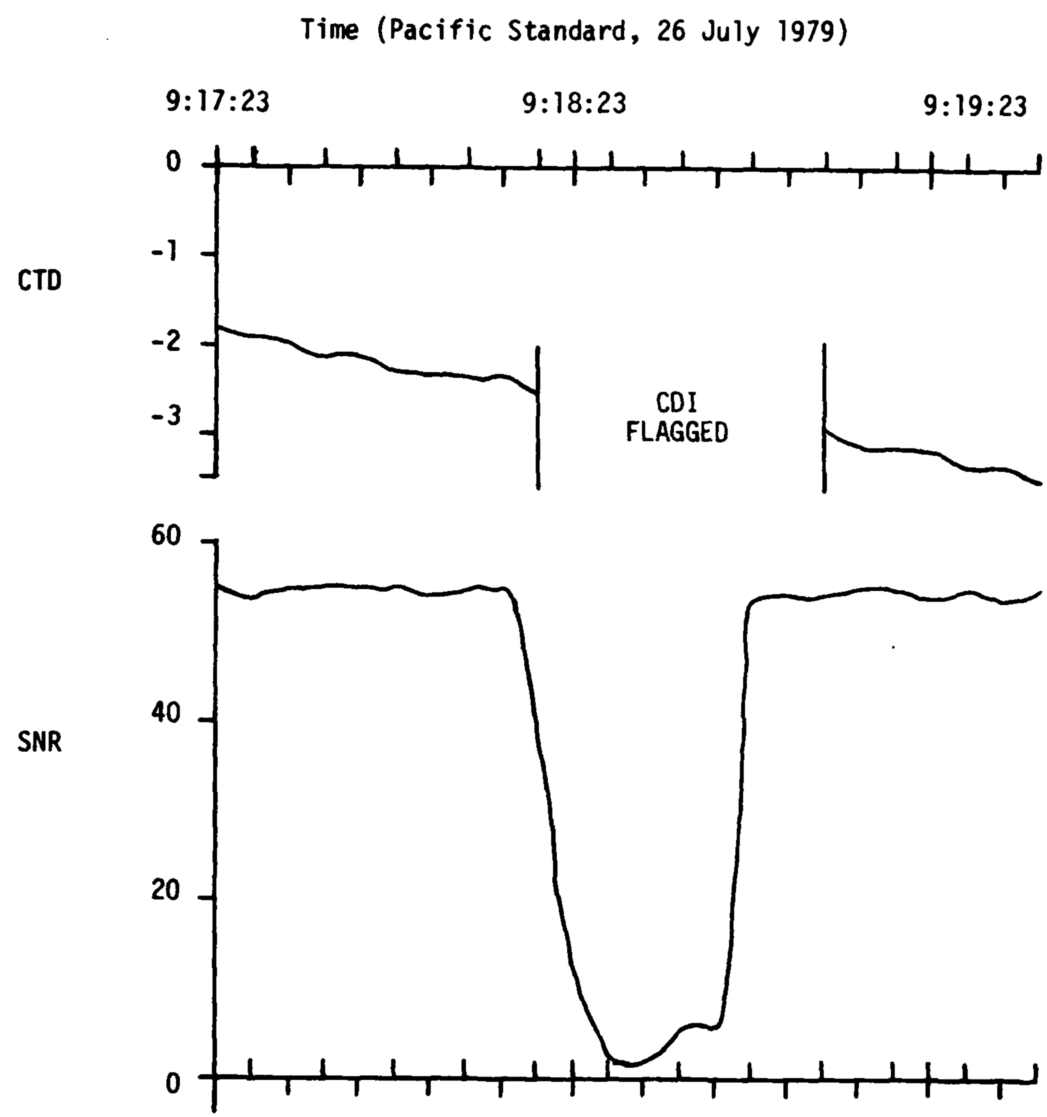

Figure C.4 Effects of Momentary Searchlight Outage

There was no inflight indication to differentiate these two events from breaks in lock resulting from other causes.